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Sustainable thermal energy storage technologies for buildings: A review

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ABSTRACT

Energy management in buildings is indispensable which would control the energy use as well as the cost involved while maintaining comfort conditions and requirements in indoor environments. Energy management is intensely coupled with energy efficiency and increasing of which would provide a cost-effective pathway for reducing greenhouse gas emissions. In recent years, the magnitude of energy consumption in buildings seems to crest from the normal demand and that has to be carefully addressed through implementing energy conservative and energy management techniques. In the class of having several energy efficient schemes, thermal energy storage (TES) technologies for buildings are increasingly attractive among architects and engineers. In the scenario of growing energy demand worldwide, the possibility of improving the energy efficiency of TES systems can be achieved from break-through research efforts. The prime intention of this paper is to review the potential research studies pertaining to a variety of latent heat energy storage (LHES) and cool thermal energy storage (CTES) systems solely dedicated for building heating, cooling and air conditioning (A/C) applications. Technical revelations regarding the integration and performance evaluation of heat storage materials in building fabric elements as well as using separate heat storage facility to satisfy the space thermal load demand have been gleaned from numerous research contributions and presented. Emphasis is also given on advanced heat storage materials produced using micro and nanoparticles to realize their improved heat transfer characteristics which would eventually enhance the overall performance of these TES systems. Furthermore, the sustainable aspects of these TES systems to gain the Leadership in Energy and Environmental Design (LEED) credentials for low carbon/high performance buildings are signified.

Contents

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1. Introduction

Energy is well recognized to be the lifeline of all human activities. In a broad perspective, energy acts as a key catalyst in the generation of wealth for a nation by making its significant role in developing the technological, industrial, economic and social sectors within the nation. It is worth to note that a well developed country with enormous energy sources and proper energy management systems can have an improved economic status than its neighboring developing countries. On the other hand, it can be seen that the demand for energy will tend to grow as the economies of the developing world rises simultaneously.

Since the energy crisis encountered in late 1970s and early 1980s there has been a continuous increase in the energy demand till now. Providing a low or constant level of energy supply towards the demanding energy status clearly indicates the alarming limit for using the conventional fossil fuel based energy sources further. The major energy challenges to be confronted in this regard can be listed as:

- growing concerns about the extensive usage of primary and secondary energies globally, imminent shortage of primary energy and its extraction
- relative green house gas (GHG) emissions to the environment, scientific evidences for climate changes and global warming impacts on the environment
- overall rise in fuel prices.

In order to sustain the living standards in developed nations as well as to improve the societal and economical status in the developing countries, it is of great importance to balance the huge gap between the energy generation and consumption. The statistical references from the International Energy Agency (IEA) and International Energy Outlook 2010 (IEO) indicates an increase in the energy demand and the world marketed energy consumption among the world nations [1] as shown in (Fig. 1(a–c)). In Fig. 1(a) it is observed that the energy demand arising from coal and oil has been reduced significantly for the Organisation for Economic Co-operation and Development (OECD) countries. The reason may be due to the fact that the OECD nations have shown greater interests towards using renewable and other non-fossil fuel based energy sources for balancing and satisfying their energy production and demand.

In Fig. 1(b) it can be seen that the world marketed energy consumption (WMEC) has been consistently increasing by 1.4% every year from 2007 onwards. In total, the WMEC would increase up to 49% indicating that the imbalance between energy production and consumption has reached the limiting point. Based on Fig. 1(c), the share of the world energy consumption for the United States (US) and China tends to reduce and increase respectively in future years, whereas for India the share of energy consumption may rise marginally. Many research contributions addressing the issues related to consumption of global and total energy, carbon dioxide (CO_2) emissions were reported and the possible ways to reduce their effects especially applied to buildings have been suggested [2–10].

Collectively, the countries with well developed energy and economic profiles can help to greatly bridge the gap present between the energy supply and demand worldwide. In this context, engineers, scientists, technologists, economists and environmentalists all over the world are in search of finding new solutions to the aforementioned energy challenges through executing quality research works. The energy challenges as presented above can be tackled effectively by performing the following activities:

- development of new energy strategies that would reduce the demand for energy, identifying energy conservative techniques to guarantee the security of the energy supply, improving the energy efficiency of the workable energy systems by implementing advanced methodologies and intelligent technologies, increase the lifetime of the energy systems by using the advanced materials that would help the system to consume less energy at all times immaterial of the ambient conditions where the energy systems are employed, promoting the use of new and renewable energy sources to offset the conventional fossil fuel based energy sources
- implementing strategic policies and planning measures for addressing the growing energy security and environmental concerns.

This paper is organized in a way to identify and present the facts related to the development and integration of various LHES and CTES systems in buildings to satisfy heating and cooling requirements. Efforts to give an update on the performance aspects of these systems have been put forward through covering a spectrum of potential research works been performed over the last three decades.

Perspectives on the global energy demand, total energy consumption in buildings, measures to overcome the energy challenges and improve energy efficiency in buildings are provided in the initial sections of the paper. The research activities pertaining to these systems done from early times to present have been surveyed and are shown graphically. The importance of integrating TES systems with building architecture is discussed.

The nucleus of this work focusing on the performance assessment of these TES systems while incorporated in buildings is largely reviewed and presented in the fourth section. Recent trends in the development of advanced phase change materials (PCMs) using micro and nanotechnology for achieving good thermophysical properties and enhanced heat storage characteristics during charging and discharging processes are also included in this section. This would make the users to become familiar to handle such micro/nano-based PCMs for building TES applications and gives an opportunity to bridge the energy gaps.

The last section gives an outline of the methodologies proposed for the effective utilizing of TES systems in high performance buildings with an emphasis on acquiring LEED credit rating and sustainability in buildings. Recommendations to take forward research activities in the heat energy storage technology are devised.

2. Energy usage in buildings

Energy production and consumption plays a vital role in deciding the energy conservation at every step of the economic development worldwide. The global total energy consumption (GTEC) can be broadly categorized as depicted in Fig. 2 and that

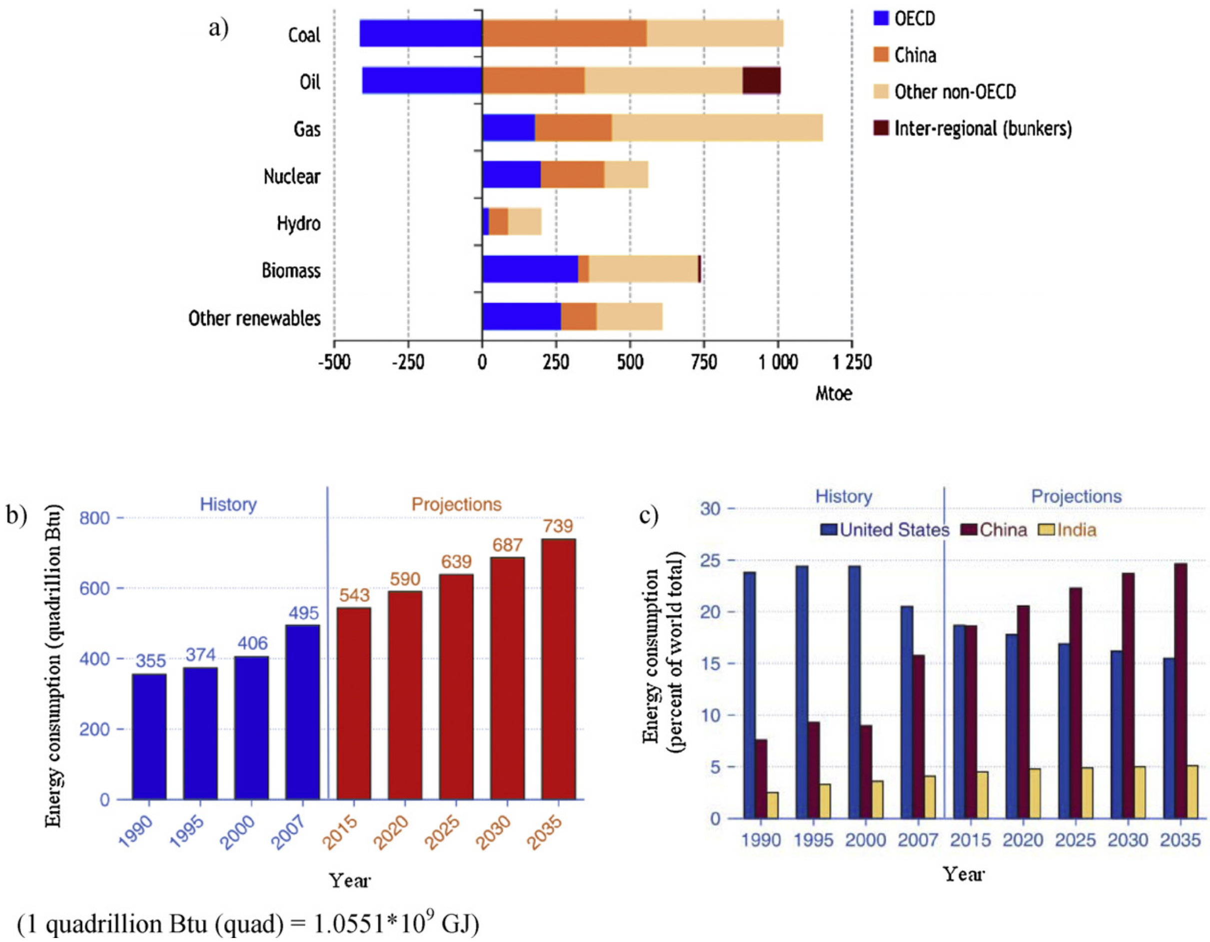


Fig. 1. Energy demand and world marketed energy consumption [1,2].

has a direct influence on the economical and environmental development. The classification of GTEC actually infers that energy consumption is an interconnected key element that has to be carefully dealt with while addressing for an energy conservative and efficient design of systems and environment.

Furthermore, the extent of energy consumed by the end-user is as most important as other categories, since it forms the baseline for generating, distributing and conserving the overall energy which in turn would facilitate for improving the economical status considerably. The continuous development of global economy

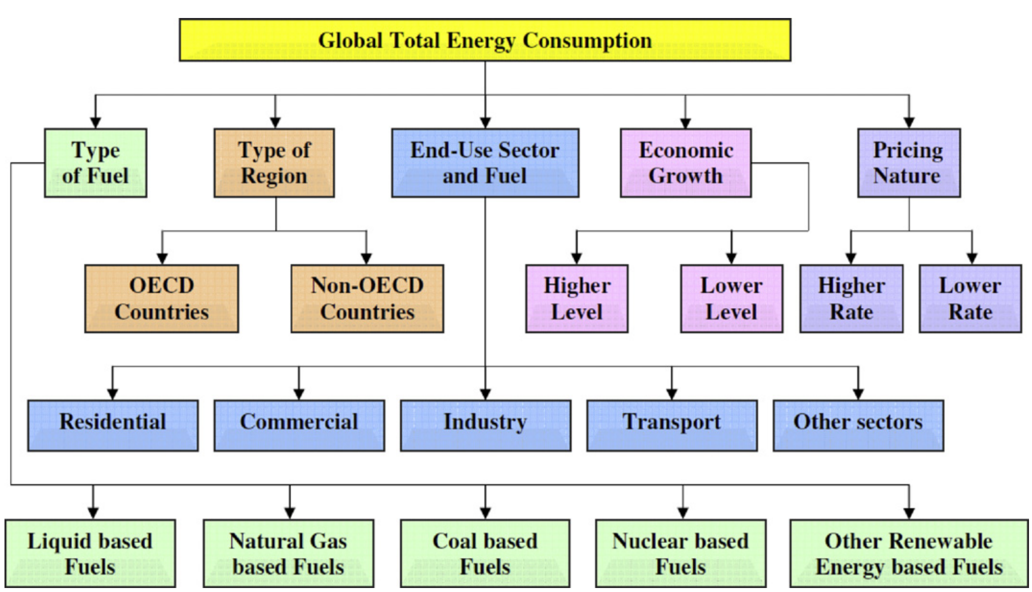


Fig. 2. Classification of global total energy consumption.

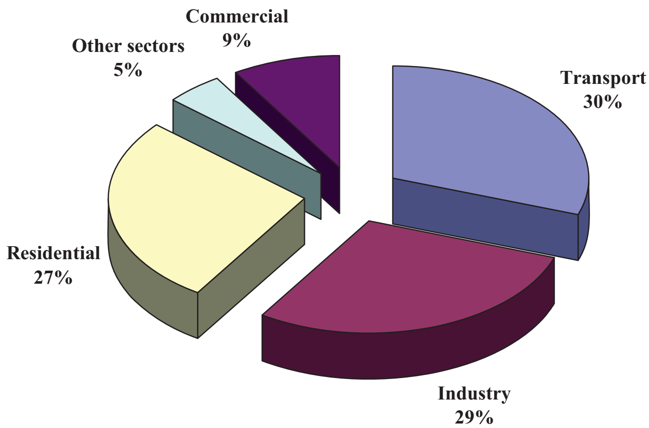


Fig. 3. Energy consumption break-up by sector wise [11].

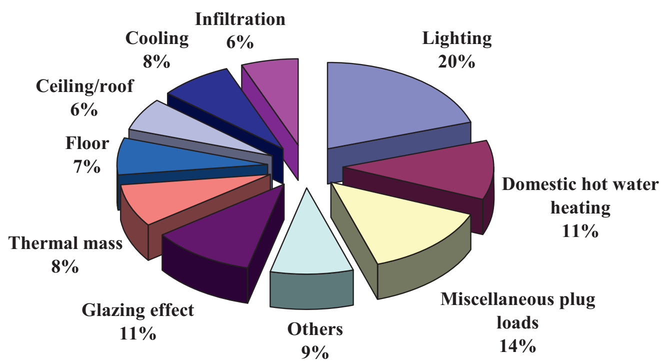


Fig. 4. Relative average break-up of end-energy usage and losses in buildings [4,5].

has paved way for the extensive usage of energy sources especially applied to the construction and development, commercial, industrial, transport and residential sectors. The break-up of energy consumption for these sectors in accordance to the IEA statistics is presented in Fig. 3. In recent years, the increased demands in the constructional sector has led to the development of elegant and huge building structures worldwide that relatively solve the required purpose but might sometimes compromise on energy consumption. According to the statistical report of IEO 2007 [11] the building sector in developed nations is accounting for about 40% of primary energy consumption, 70% of electricity use, and 40% of atmospheric emissions including greenhouse gases. It is interesting to note that, buildings would consume one-quarter to one-third of the overall energy generated globally. The relative average break-up of end-energy usage and losses in buildings is represented in Fig. 4 and the global annual primary energy consumption by buildings presented in Table 1. In particular, the inherent end-energy usage and energy losses that might occur in due course of time of operation have to be determined in buildings to make them energy efficient.

Table 1
Estimated annual primary energy consumption worldwide by buildings [12].

Year	Energy consumption (quads/year)
2004	72.2
2010	82.2
2015	90.7
2020	97.3
2025	103.3
2030	109.7

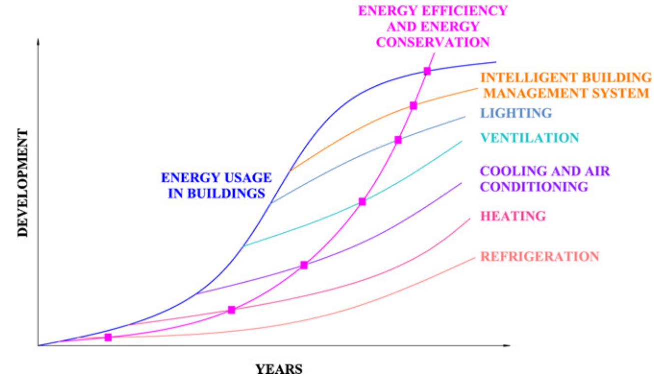


Fig. 5. Technological development of engineering fields related to building energy usage over years.

2.1. Energy efficiency and energy conservation (EEEC)

The concept of energy efficiency is indispensable in many engineering applications and in fact has a strong relationship with the per capita energy consumption and economic growth rate. The term energy efficiency refers to the amount of energy actually required to generate or produce the desired end products. In other words, energy efficiency is a parameter that indicates the minimum level of energy usage for performing an associated task and that largely depends on the state-of-the-art technological and production processes.

Energy efficiency is highly valued in almost all engineering and technological fields because of the workability of end-use product that consume less energy on long term basis. In recent years, energy efficiency is gaining its momentum especially in the building services engineering starting from the scheme inception to the construction stage of the building. It is certain that EEEC are interrelated and meant for minimizing the energy usage in mainly in the form of heat gain or heat loss in buildings.

The development of major engineering fields pertaining to the critical aspects of building energy usage with respect to the growing years is graphically presented in Fig. 5. Based on Fig. 5 it can be interpreted that various techniques addressing occupant comfort requirements in buildings in terms of maintaining good thermal environment, better indoor air quality (IAQ), excellent illumination facilities etc. emerges from the S-shaped baseline of energy usage. Increasing energy efficiency may add to the first costs of building. The energy-cost savings potential experienced from the building over time usually lessens the effects induced by the first costs [12–20].

In short, a good and well constructed building must satisfy the expected comfort requisites of occupants without sacrificing the energy efficiency and energy conservation. This is the reason for which the curve EEEC passes through all the major fields and indicates the relevance of implementing EEEC measures at every stage of development of buildings.

2.2. Cooling, heating and ventilation in buildings

Ever since the ancient times, the use of cooling, heating and ventilation concepts in buildings are increasingly attractive till now. By the influence of continuous technological developments these concepts have gained impetus and intended primarily to promote comfortable environment for people living in the new and existing buildings. In order to bring these concepts work in reality several engineering systems are being developed in much energy efficient way. Collectively, the engineering systems that are meant to fulfill the objectives of providing good thermal environment with

better indoor air quality are categorized as heating, ventilation, air conditioning and refrigerating (HVAC&R) systems.

Generically, cooling load in buildings refers to the heat energy that is actually required to be trapped off from the zone(s)/space(s) to be cooled or conditioned and dissipating the retrieved heat out of the zone(s) to the ambient. Heating in buildings is achieved by supplying heat energy to the zone(s) to drive off the cold energy contained within the zone(s). On the other hand ventilation and air conditioning (A/C) in buildings are relatively important in terms of achieving effective building performance and occupant comfort conditions. Design and selection of proper ventilation strategy in buildings must be capable of providing safe, healthier, productive and comfortable working environment to occupants.

Research studies that deals with accomplishing good thermal comfort and improved indoor environmental conditions attributed to the improved energy savings of HVAC systems were performed, in recent years [21–24]. Employing advanced intelligent logical control mechanisms into the integrated building management systems would enable the modern HVAC systems to perform better than the conventional systems. Advantage of using these controllers for HVAC systems in buildings were elaborately discussed by Ahmed et al. [25], Karunakaran et al. [26], Parameshwaran et al. [27]. More information pertaining to development of building energy regulations for HVAC systems along with its scope and requirements can be obtained from [28]. The overall diversity of HVAC systems in buildings meant to provide comfort conditions for occupants is depicted in Fig. 6.

3. Latent heat energy storage (LHES) system in buildings

Increasing energy demands and environmental concerns worldwide has noticeably paved way to the development of many energy saving measures during the past three decades. As pointed out in the earlier sections building sector would tend to consume more primary energy than any other sectors, at all times. Although there are several measures available to minimize the net energy consumption in buildings, there is still a need for an efficient system which can offset on-peak thermal load demand with better energy savings potential. In this perspective, TES offers better capability to store available heating and cooling energy in off-peak load conditions to effectively match the on-peak demand periods. TES integrated with thermal systems allows for using thermal energy effectively and facilitates for energy substitutions at large scale.

3.1. Progress of research activities

Innovative and dedicated research works being performed on LHES systems for the past three decades has been the key factor for its development and subsequent penetration into building sector. In view of the increased concerns on energy savings, it could be seen from Fig. 7(a) that the percentage of research publications on LHES systems for building applications has gradually increased over the period of time. In 2010, the percentage of research publications achieved the maximum that is, around 21 focused on integration of LHES system in buildings. Fig. 7(b) shows the split-up pattern of research publications for LHES system dealing with building HVAC applications.

It is interesting to observe that the research methodologies adopted in development of latent heat storage materials (LHSM) have climbed up to the maximum, in recent times. On an average, the articles published on space heating, space cooling using building fabric, free cooling, air conditioning, LHSM, nano-based LHSM and review works were found to be 112 till date. This value is expected to augment considerably in the imminent future with the growing demands for nanotechnology applications. LHES technology is known from the ages and has been functioning effectively in numerous thermal applications. One such application is where incorporation of LHES in buildings has revealed potential benefits in

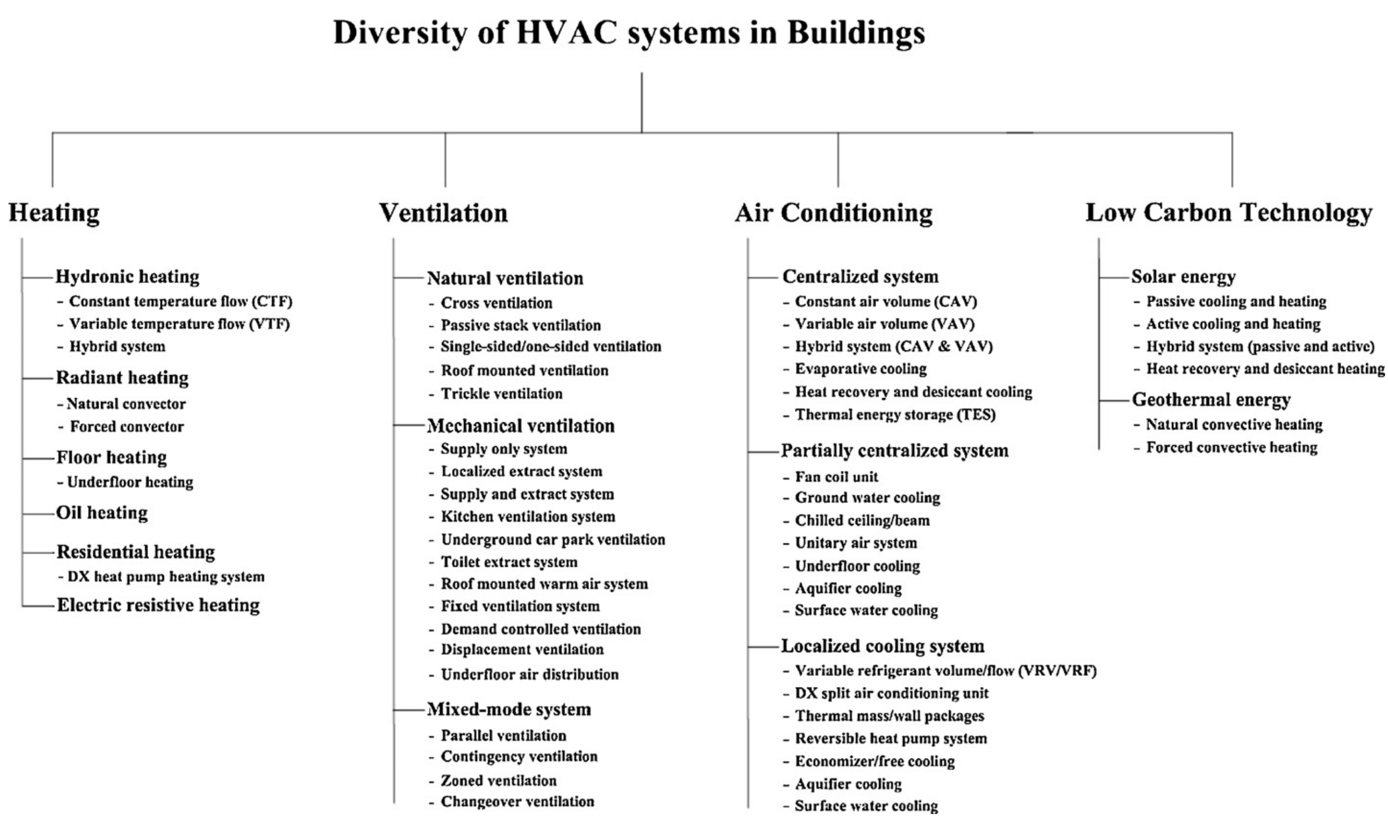


Fig. 6. Overall representation of HVAC systems in buildings.

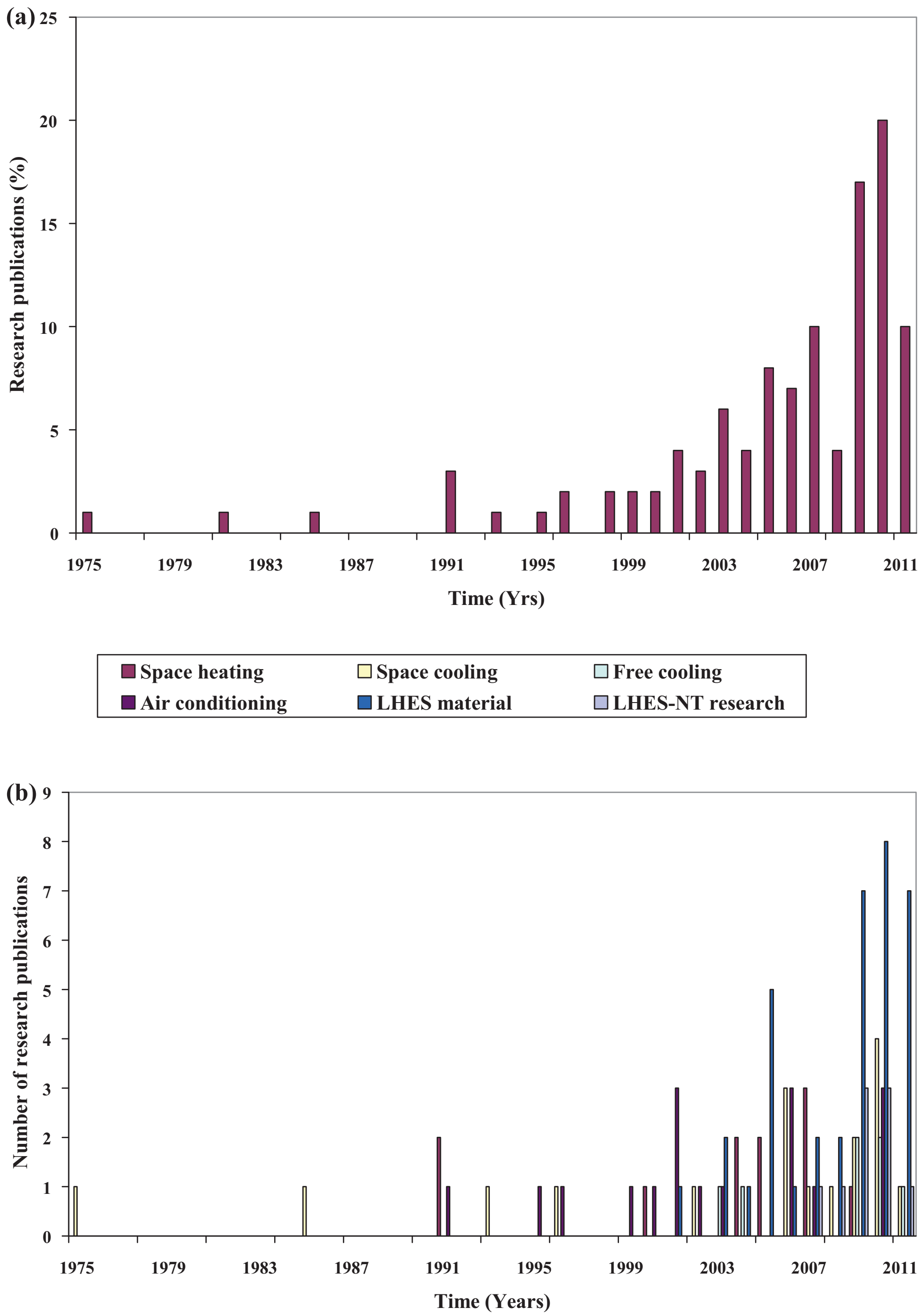


Fig. 7. Progress of research activities a) yearly publications and b) HVAC system based yearly publications.

terms of storing and releasing heat energy based on fluctuated load demand at lower overall energy [29–32]. By introducing suitable latent heat storage material into building thermal mass or fabric structure the temperature fluctuations in indoor environments can be minimized [33].

The use of LHES system to capture the cold energy from ambient air in night time and discharge the stored energy during day-peak load periods is increasingly attractive, in recent years. This is usually termed as free cooling or economizer ventilation technique. Interesting research works pertaining to this technique have been performed to achieve passive cooling and ventilation in buildings [34,35].

3.2. Integration with building elements and systems

LHES systems are primarily intended for enhancing the performance of thermal systems and to store and release heat energy on short-term or diurnal or seasonal basis depending on the thermal load requirements experienced in buildings. LHES systems combined with building elements and systems find its potential usage in cooling and heating applications. Variety of research works pertaining to the implementation of LHES system to substitute cooling, heating and air conditioning load requirements in buildings have been reviewed and presented in Table 2 .

Table 2
Integration of LHES systems in buildings.

Application potential	LHES system integration in building/system	LHES system type	Functional aspects of LHES system in building	Methodology	Reference
Space heating	Internal wall construction	Passive	Diurnal/short-term heat storage from direct heat gain in a residential building room	Simulation	Peippo et al. [36]
	Facade panel	Passive	PCM blended with glazing panels to improve daylighting, space heating and thermal comfort in winter; reduces peak cooling loads in summer	Experimental	Weinlader et al. [37]
	Floor component	Passive	Cost-effective novel form stable PCM containing microencapsulated paraffin regulates indoor temperature	Simulation	Li et al. [38]
	Internal wall and ceiling construction	Passive	PCM implanted gypsum boards to store heat energy from existing electrical facility in office space; shift on-peak space heating demand and conserve overall electrical energy	Experiment	Qureshi et al. [39]
	Floor component	Passive	Cost-effective shape stabilized PCM plates stores heat in night time using off-peak electricity to compensate on-peak space heating demand in daytime	Experiment	Lin et al. [40]
	Floor component	Passive	Gypsum–concrete PCM mixture as complete and partial carpets included into building flooring regulates floor surface temperature	Simulation and experiment	Athienities and Chen [41]
Space cooling	Brick construction	Passive	Encapsulated PCM offsets cooling demand from building; to conserve overall electrical energy consumption and reduce CO_2 emission from building	Experiment	Castell et al. [42]
	Ceiling mounted	Passive	PCM stores cool energy from ambient air during night time for meeting out daytime cooling demand	Experiment	Zalba et al. [43]
	Exterior wall	Passive	PCM-doped color coatings applied on building exterior fabric minimizes indoor temperature variations, reduces building thermal load; to maintain thermal comfort conditions in indoor space	Experiment	Karlessi et al. [44]
	Ceiling mounted	Passive	Night ventilation scheme amalgamated with PCM packed bed storage reduces room temperature in day hours and conserve energy spent on cooling and ventilation	Experiment	Yanbing et al. [45]
	Floor component	Passive	PCM granules made of glass beads and paraffin waxes stores large cooling energy in night time to release it upon demand during day-peak load periods	Experiment	Nagano et al. [46]
	Ceiling mounted	Passive	Two separate LHES systems containing sphere encapsulated PCM stores cool energy to reduce heat gain from ventilation air and room return air; save overall building energy, regulate indoor temperature and reduce size of mechanical ventilation system	Experiment	Arkar et al. [47]
	Brick construction	Passive	Brick element mixed with PCM to absorb direct heat gain and reduces temperature fluctuations in indoor environment	Simulation and experiment	Alawadhi [48]
	Ceiling mounted	Passive	PCM integrated with air heat exchanger to cool indoor air during day-peak load conditions with stored cool energy in night time	Experiment	Lazaro et al. [49]
	Ceiling panel	Passive	Ceiling panels embedded with PCM to cool indoor environment	Experiment and simulation	Koschenz and Lehmann [50]
Air conditioning	Air handling unit	Active	Ice-cool energy storage combined with cold air distribution reduces running cost and save total energy	Experiment	Tassou and Leung [51]
	Heat pipe	Active	Ice storage combined with helical heat pipe having better solidification and melting characteristics; extracts heat load from indoor space and conserve overall building energy	Experiment	Fang et al. [52]
	Thermal battery	Active	Cold storage integrated with thermal battery improves thermal performance of air conditioning system	Theoretical and experiment	Chieh et al. [53]
	Air handling unit	Active	Ice-cool thermal storage system compared with other cool storage systems using fuzzy multi-criteria technique for overall performance evaluation	Simulation	Jiang et al. [54]
	Fan coil unit	Active	Spherical PCMs packed bed blended with ice-cool thermal storage enhances performance of air conditioning system	Experiment	Fang et al. [55]
	Radiant cooling unit	Active	Ice thermal storage incorporated with air conditioning system augments the combined effect of radiant cooling and air conditioning in indoor environment	Experiment	Matsuki et al. [56]
	Ejector unit	Active	Cold storage included with solar-assisted ejector unit improves cool thermal storage capability and overall air conditioning system performance	Simulation	Diaconu et al. [57]
	Air handling unit	Active	Cold storage facility provides optimal control over indoor cooling with increased cost-energy savings and improved thermal capacitance in building	Modeling analysis and simulation	Kintner-Meyer and Emery [58]

Table 2 (*Continued*)

Application potential	LHES system integration in building/system	LHES system type	Functional aspects of LHES system in building	Methodology	Reference
	VAV-air handling unit	Active	PCM based thermal energy storage system incorporated with air conditioning system achieves good thermal comfort and indoor air quality in buildings without sacrificing energy efficiency	Experiment	Parameshwaran et al. [59]
	District cooling system	Active	Ice storage system implemented with district cooling facility minimizes overall energy-cost issues related to buildings and conserve energy	Simulation	Chan et al. [60]
	District cooling system	Active	Improved thermophysical properties of PCMs in a cool thermal energy storage system integrated with district cooling facility reduces chiller size, issues related to peak thermal load-shifts and cost-energy management in buildings	Experiment	He et al. [61]
	Vertical ground source heat exchangers	Active	Cool thermal energy storage integrated with earth heat exchangers and cryogenic cooling system achieve desired space cooling and energy savings	Experiment	Hamada et al. [62]

Table 3
Summary of key manufacturer of PCM worldwide [184].

Manufacturer and reference	Range of PCM temperature (°C)	Number of PCMs (available within the given temperature range)
RUBITHERM [63]	−3 to 100	29
Cristopia [64]	−33 to 27	12
TEAP [65]	−50 to 78	22
Doerken [66]	−22 to 28	2
Mitsubishi Chemical [67]	9.5 to 118	6
Climator [68]	−18 to 17	9
EPS Ltd [69]	−114 to 164	61

3.3. Apposite thermal storage materials

PCMs are a class of materials that exhibits relatively good heat transfer characteristics by undergoing cyclic freezing and melting processes by the influence of heat transfer medium (fluid or liquid). Latent heat energy content drives PCM to change its phase (liquid to solid or vice versa) at isothermal conditions and that enable PCM to store or release heat energy depending on the thermal load demand. In practice, PCMs that possess high latent heat of fusion, high thermal conductivity, high density and better heat transfer properties are mostly preferred. Most of the conventional PCMs available are grouped under three main categories like salt hydrates, paraffins and fatty acids.

In this context, phase change material (PCM) based thermal energy storage systems are developed in order to stabilize the temporal variations in temperature while exchanging heat energy from the heat transfer medium. Appropriateness of PCMs for thermal storage mainly depends on the type of heat storage system, charging and discharging time periods based on thermal load profile of building. Generalized classification of PCMs with respect to their operating temperature and potential manufacturers are specified in Table 3. Thermophysical properties of some commonly used PCMs in LHES systems are largely presented in these studies [70–73], which would be of relevance to the engineers and researchers involved in LHES systems design.

4. Performance evaluation of LHES system in buildings

Implementation of LHES system as applicable to specific thermal load requirements in buildings depends on to satisfying required cooling or heating load demand, methodology of heat storage, melting and freezing attributes of PCMs, spatial requirements for HVAC plant and overall cost-energy savings potential. Foremost step in achieving energy efficiency in buildings using LHES system would be on the part of experienced design, selection and performance evaluation of these systems. In the key design phase, intended operating schemes, control methodologies as well as mode of operation of the LHES system has to be taken into account.

Once the thermal load profile has been generated and the type of storage system is ascertained the LHES system can be sized effectively. Assessment of total capacity of LHES system and the interaction of building elements during thermal cycling for a given load profile would basically stand onto the side of effective design process. For instance, in an underfloor cooling and heating systems design the value of maximum load per unit area of floor has a significant role especially while integrating the LHES system. Generically, the values of maximum thermal load for cooling and heating schemes are 40 and 100 W/m^2 respectively. Thus, by properly selecting the thermal load sharing between the underfloor and LHES systems the required comfort conditions in indoor environment can be effectively accomplished.

In case of building fabric integrated LHES system the net area of PCM panels or slabs exposed to indoor air would determine the



Fig. 8. Photographic view of PCM tiles [76].

capacity as well as the rate of melting and freezing aspects of the system. Fan assisted active systems can increase the contact area between indoor air and the panels/slabs and would perform better than passive systems. Approximately 50% of per day total cooling load can be catered with ice-cool thermal energy storage (ICTES) system being incorporated with the base load chillers installed in buildings [74]. Effective utilization of LHES systems in buildings based on their performance are elaborately discussed in the following sections.

4.1. Passive systems

Passive LHES systems design would glean the merits of naturally available heat energy interactions in order to maintain the comfort conditions in buildings and minimize the usage of mechanically assisted heating or cooling systems. Various options are available for passively designing a building integrated with LHES system in regard to heating and cooling cycles based on the thermal load demand (profile). These may include increased use of façade panel skylight design, thermal mass, shading effect using fins, coated glazing elements, solar heating and free cooling (night ventilation) techniques.

In recent years, the effective use of PCM impregnated wallboards in interior wall surfaces of building enclosure has gained impetus in maintaining the desired thermal environment in indoor environments. In this context, a comparative study between an ordinary room and phase change wall room was conducted by Shilei et al. [75]. Capric acid and lauric acid (fatty acid based) mixture in the proportion of 82:18% having freezing and melting temperatures of 19.138 and 20.394 °C was used as the PCM in this study. It has been observed that the room integrated with this PCM impregnated wallboards showed good performance in terms of maintaining the warmth and thermal comfort during winter. The heat loss effects from the room to the ambient in winter were minimized effectively. Also, the energy consumption rate of electrical heating utilities was reduced significantly.

A new kind of PCM based tiles meant for stabilizing the indoor air temperature in winter was developed and patented by Ceron et al. [76]. Photographic view of the PCM tiles is shown in Fig. 8. This PCM tiles would absorb the heat energy from sunlight in daytime and store them as potential heat source for warming up the house during night time. Based on the analysis report it is seen that by varying the temperature of fusion the same PCM tiles can also serve as a heat sink in hot sunny days in summer. Collectively, this PCM tiles could contribute for overall energy conservation in buildings by means of passive cooling/heating. Many research works including simulation and real time experimental investigations have been performed since 1995 in implementing PCM wallboard elements in building interiors. The main objectives of these studies were to balance the effects caused by indoor temperature fluctuations through phase change wallboards and to maintain comfort for building occupants as well [77,78,87,89,91,94].

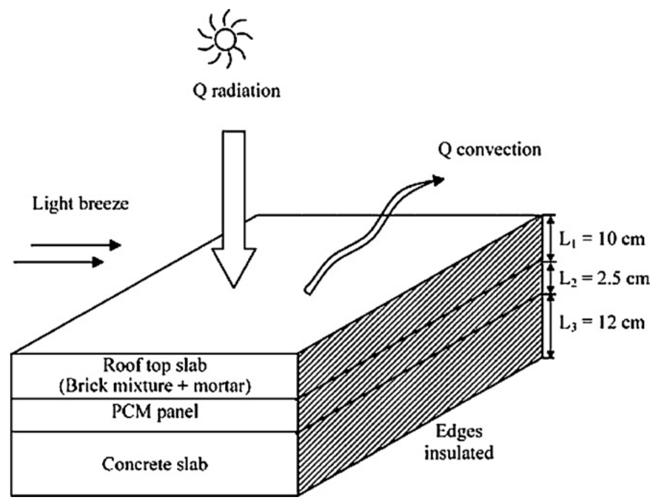


Fig. 9. Sketch of building roof integrated with PCM panel [79].

Pasupathy and Velraj [79] carried out a different approach to determine the thermal performance of building roof structure subjected to seasonal variations using double layered PCM arrangement. The test model building room was located in a hot and humid climatic region (Chennai, India) and the double layered PCM panel was configured in between the roof top slab and concrete slab. For all testing cycles, thermal performance of building roof was appreciably good and the temperature variations in the room were reduced substantially. This is attributed to the double layered PCMs having its fusion temperature kept at 6–7 °C above the average temperature of ambient air during early morning cold periods. Sketch of the PCM integrated roof structure is shown in Fig. 9. This system possibly assists to shift the peak load demand and could save much energy in buildings on a year-round operational strategy.

Thermal gains entering into indoor space from hot outdoor ambient can be appreciably reduced by the building roof structure embedded with PCM filled cone frustum apertures as proposed by Alawadhi and Alqallaf [80]. P116, n-eicosane and n-octadecane are the PCMs used in the analysis with melting temperature and latent heat of fusion values of 47, 37, 27 °C and 225, 241 and 225 kJ/kg respectively. Parametric investigations performed on various geometries of PCM reveal that each PCM depending on its fusion properties has kept the roof temperature at moderate level which is quite lesser than the outdoor conditions. Likewise, the peak heat flux was reduced by 39% for the case of n-eicosane PCM. Frustum type conical holes actually participated in augmenting the

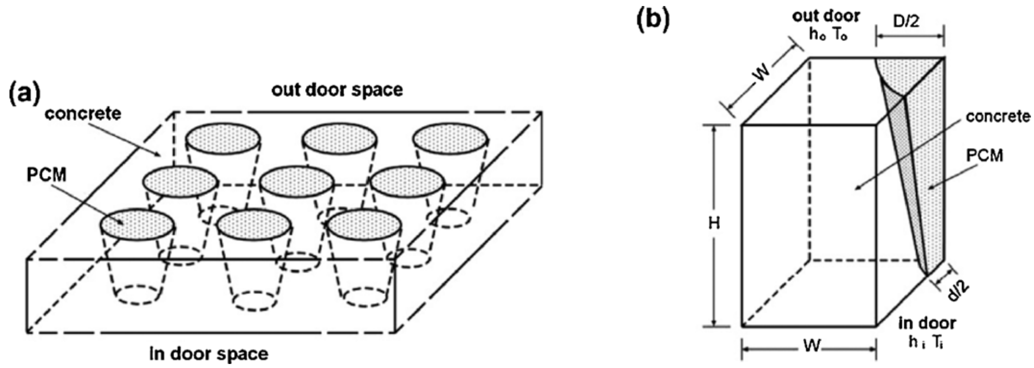


Fig. 10. (a) Schematic representation of the PCM filled conical apertures on roof structure, (b) computational domain, essential geometric parameters and boundary conditions [80].

convective heat transfer rate between the indoor air, PCM and outdoor air in early morning periods through peak load (working) hours. It is suggested that conical type holes containing PCMs constructed on roof structures would help to minimize the heat gain effects and temperature swings in indoor environments. Schematic representation of PCM filled conical aperture on roof with modeling details are shown in Fig. 10.

Ahmad et al. [81] introduced a method to combine the potential benefits of vacuum insulation panel (VIP) and PCM panel associated to VIP for augmenting the thermal storage capacity of lightweight wallboards utilized in building interiors. Polyethylene glycol (PEG) 600 was the PCM used which possess melting temperature in the range 21–25 °C and latent heat of fusion around 148 kJ/kg. View of the VIP-PCM panel arrangement with test cells is described in Fig. 11. Two test cells finished with high quality insulated lightweight wallboards interiors were considered for the numerical and experimental investigation. Of the two test cells, one test cell was provided with PCM panels and each PVC panel made of the PVC alveolar was filled with 20 kg of PCM and fixed into appropriate position in the test cell.

The PCM test cell show exceptional thermal performance and reduced indoor temperature to over 20 °C during hot seasonal conditions. During winter, the test cell with PCM was at −6 °C whereas the test cell without PCM was at −9 °C. This signifies its heat storage capabilities and high efficiency. Solutions of numerical simulation and computational modeling obtained from TRNSYS software were found to comply with experimental results, thus validating the numerical model developed. Based on this study, wallboards

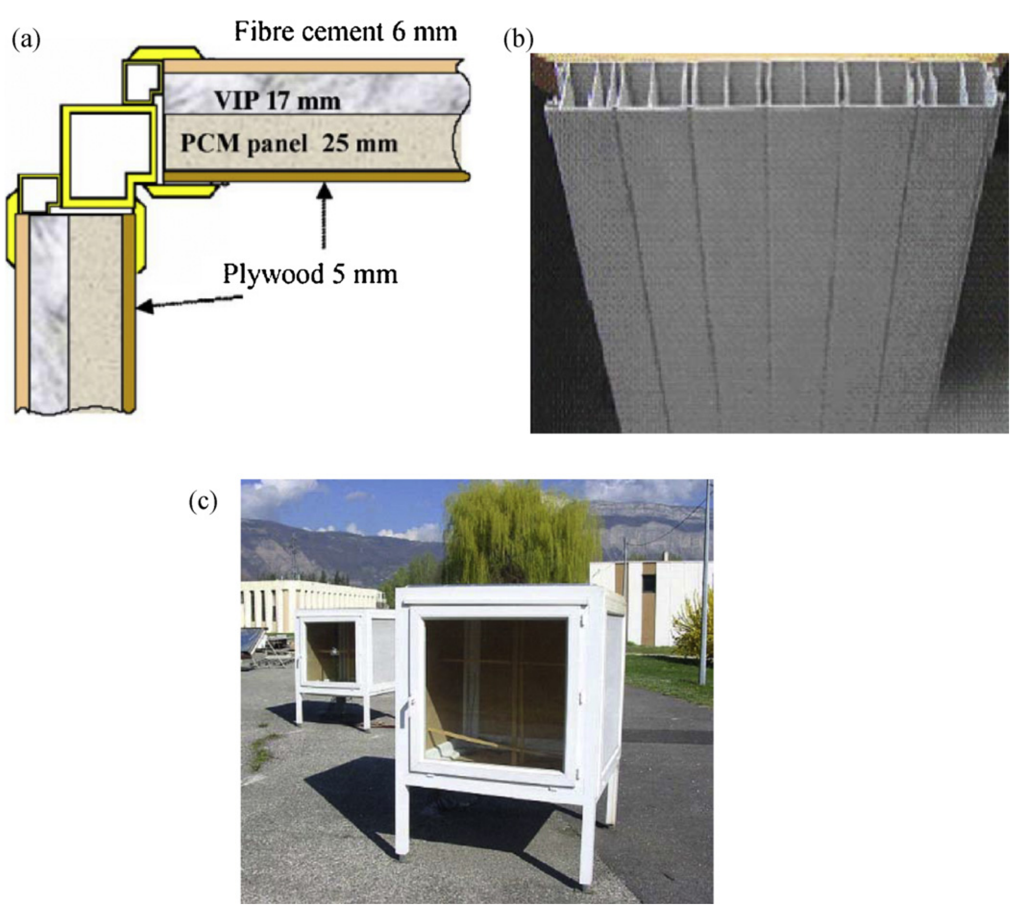


Fig. 11. (a) Sketch of test cell containing PCM, (b) photographic view of PVC panel, (c) external view of test cells [81].



Fig. 12. Dividing wall with 16 glass bricks infused with PCM [84].

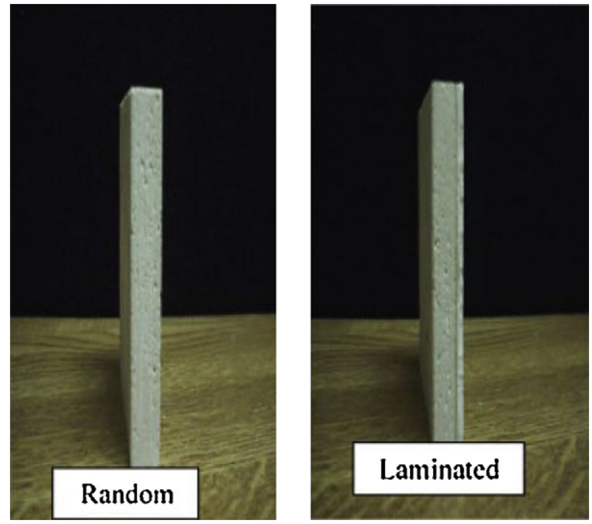


Fig. 13. Samples of drywall [90].

coupled with PCM interiors can be regarded as good candidates for storing and releasing heat energy throughout the year.

Numerical and experimental validations pertaining to the encapsulated PCM flat slabs, PCM concrete duct system and glass bricks filled with PCMs for passive building cooling applications have been presented [82–84]. The models developed in these studies deals with one dimensional heat transfer rate between the PCM plates and HTF, convection effects as well as thermal response of the PCM. Simulation outputs predict that the thermal performance of PCM plate, concrete duct and glass brick structures are in good agreement with experimentally measured values and confines to the governing equations and boundary value conditions. Temperature lag, specific heat capacities and convection heat transfer rate of these PCM assemblies were also taken in account in the analysis, which helped to realize the energy efficiency of cooling and air conditioning systems in buildings through these PCM elements. Pictorial representation of dividing wall with 16 glass bricks infused with PCM is depicted in Fig. 12.

Zhu et al. [85] modeled a shape stabilized PCM (SSPCM) wall system and progressed with quantitative analysis on the energy performance and optimal control strategies for a real time building A/C system using this SSPCM envelope. Peak thermal load shaving and demand limiting control methodologies were examined based on the SSPCM thermal properties and characteristics. Two tropical climatic regions (Hong Kong and Beijing) with thermal load profiles were selected for analysis. Simulation of SSPCM enveloped buildings located in these regions show improved thermal performance and indoor thermal comfort under time-based and energy-plus-demand-based pricing policies.

For the former and latter pricing policies, the electricity costs of these buildings were decreased by 11.44% and 11.29% and 10.61% and 12.76% in Hong Kong and Beijing summer conditions respectively. Using demand limiting control strategy the peak electrical demand for these buildings were reduced by 17.36% and 20.28% respectively in summer which gives an indication for using the SSPCM for achieving energy efficiency in buildings. The influence of peak heat flux on room frame walls subjected to cooling load was investigated using paraffin and hydrated salt PCMs [88]. Paraffin and hydrated salt PCMs were mixed in concentrations of 10% (paraffin-hydrated salt combination) and 20% (only paraffin) by weight in the cellulose insulation of the wallboard constructed inside the room space. Test results infer that by increasing the proportion of paraffin the PCM was capable of reducing the peak heat flux to a greater extent. The thermophysical properties of both PCMs were responsible for decreasing the heat load demand and indoor temperature swings thereby; creates a comfortable living environment in the interior space of the building.

Thermal behavior of PCM for heating and cooling applications was assessed so as to amalgamate it onto the drywall elements in indoor spaces of buildings [90]. Two PCM–gypsum boards having 11.8% of PCM concentration were considered for testing; of which one was produced with randomly distributed profile and the other with laminated profile. Fig. 13 illustrates the fabricated drywall samples made of gypsum and paraffin-based PCM. Upon testing, it was observed that laminated PCM–gypsum board performed better than randomly distributed PCM board. Nearly 55% of effective phase change reaction and 27% higher latent heat discharge capacity was experienced by the laminated PCM board than the randomly distributed PCM board.

In spite of the prevalent range of peak transition temperatures and phase change features of paraffin-based PCMs, the inherent non-symmetrical thermal profiles present in this PCM has produced incongruent effects which decelerated the phase change process. For real time cooling/heating applications using wallboards specifically made of this PCM has to be tested for several thermal cycles by applying distinct boundary conditions pertaining to the rate of heat transfer and phase change process. Inclusion of thermal fortification materials would help to bring in exact phase change characteristics at the desired temperature range as well as improve the effectiveness of these wallboards.

Shilei et al. [92] executed a similar investigation as that of [75] and their results show improved thermal performance of PCM wallboards while applied onto the interior wall surface of building. The PCM wallboard with improved thermophysical properties been developed is capable of catering on-peak cooling and heating load demands effectively. Chen et al. [93] produced a new type of high performance PCM wallboard to offset the building cooling load effectively. They studied the heat storage and energy savings potential of this wallboard using mathematical modeling and experimentation.

Outcome of their results indicate that the energy storage or release capacity of new PCM is much higher than the conventional gypsum and concrete building materials considered for the analysis. Furthermore, for having an optimal thickness of the new PCM to 30 mm with latent heat of fusion of 60 kJ/kg energy savings potential can be increased from 10% to 17% higher than other materials. This new PCM would also restrict the daytime heating effects in indoor spaces due to solar radiation by 1 °C than the other two sample materials and maintain the room at 24 °C in heating seasons. The

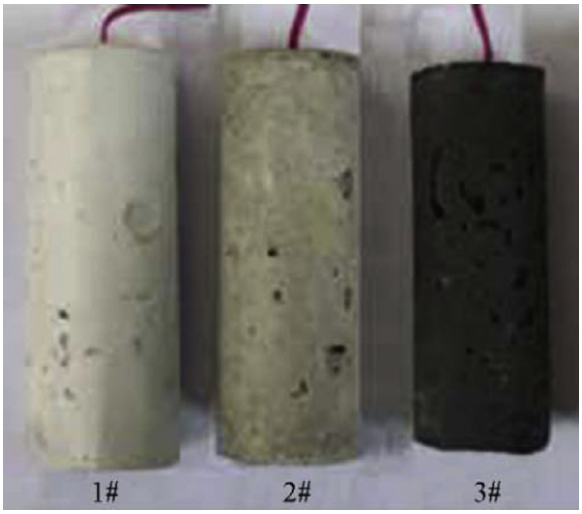


Fig. 14. Pictorial view of samples of: 1# – gypsum, 2# – cement, 3# – new PCM [93].

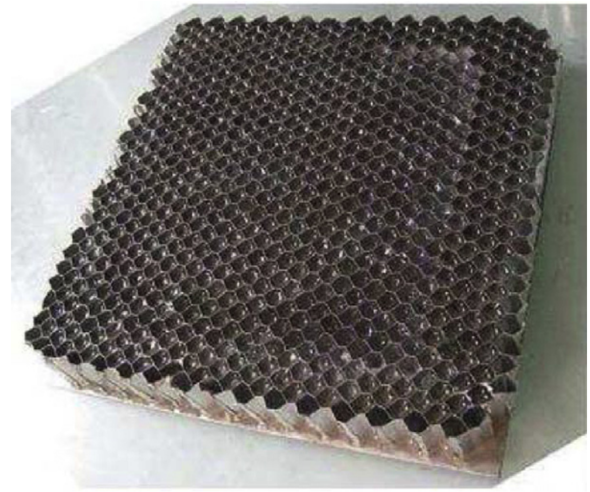


Fig. 15. Photo of honeycomb panel filled with paraffin PCM [97].

pictorial representation of three samples investigated is depicted in Fig. 14. The selection and application of this type of wallboards in practical building thermal systems calls for more attention in terms of conducting basic research and experimental procedures incessantly.

The usefulness of capric acid and lauric acid eutectic mixtures as potential PCM for heat storage in buildings was identified by Shilei et al. [95]. In their work, gypsum material was soaked in 65.12% capric acid and 34.88% lauric acid mixtures for about 10 min. The weighted quantity of PCM mixture absorbed in gypsum amounts to 26% of total weight. The PCM wallboard constructed with this configuration was tested for 360 thermal cycles and performance evaluation was done. Even after 360 transition cycles the PCM wallboard has not flawed and yields latent heat of fusion value of 35.068 J/g with fusion temperature of 18.353 °C. These features made the PCM to be thermally stable and allow it to be used for long time heat storage applications in buildings. Thermal characterization and heat storage capacity of distinct PCMs were examined by Borreguero et al. [96]. They have simulated and tested various PCM contents and reported that thermal conductivity of gypsum was autonomous on contents of wallboard microcapsules and present its value in the standard range of available literature references. Besides, they concluded that higher the content of PCM in wallboard, higher would be the heat storage capacity. In addition, gypsum block containing 5% microcapsules would reduce the thickness of gypsum by 8.5% without changing its insulating effects. These performance parameters justified the effective usage of wallboards of this kind in buildings to conserve energy and ensure comfortable indoor environment to occupants as well.

Hasse et al. [97] tried using aluminum honeycomb like structures as fins to enhance the heat transfer characteristics of paraffin PCM for offsetting heating and cooling load demands in buildings. Photograph of the honeycomb panel filled with paraffin PCM is illustrated in Fig. 15. Their results infer that the paraffin PCM exhibited heat of fusion of 170.1 and 168.1 kJ/kg at a fusion temperature of 27 °C during heating and cooling cycles. In addition, they performed numerical simulation using COMSOL Multiphysics environment and observed that the experimental results show good agreement with the numerical solutions. Thermal inertia, heat energy storage and release rates were found to increase whereas the wall surface temperature of PCM was maintained close to that of indoor comfort temperature. This indicates the suitability of their honeycombed structured paraffin PCM wallboard to be used as possible latent heat storage system for efficient heating and cooling applications in buildings.

For predicting the heat interactions in PCM subjected to transient thermal load conditions theoretical and numerical simulation was done wherein the non-linear heat transfer characteristics of the PCM were reported by Zhang et al. [98]. PCM wallboard subjected to indoor heat flux and temperature gradient shows energetic performance that was attributed to the process specific parameters defined in the numerical analysis. The two constituent parameters namely, modifying factor of the inner surface heat flux (α) and thermal energy storage fraction (b) determined the phase change and thermal performance of PCM wallboard. For all values of $\alpha < 1$, by fixing proper fusion temperature and having lower and higher values of thermal conductivity and latent heat of fusion respectively, the external wall of PCM responded well to the outdoor conditions and reduced the energy consumption significantly.

On the other hand, the inner wall of PCM also contributed for energy savings for the same conditions as above but for the selected value of thermal conductivity of PCM based on the indoor heat flux. The study gives an insight on the thermal performance and behavior of PCM which could be used in building wallboards and floor surface as well. Further to add on the part of improving overall building energy efficiency and conservation, several research works concentrating on the development of PCM wallboard fixtures and thermal mass structure have been executed through various numerical and experimental analyses [86,99–105].

From the perspective of energy efficient design, increasing the thermal mass of buildings using PCM has been found viable in modern buildings. These passively designed buildings would possibly reduce the energy consumption rate of heating and cooling equipments considerably. Diaconu [106] set forth a PCM-enhanced wall system in the building envelope evaluated the performance of the system under four distinct occupancy profiles influenced with and without ventilation scheme. Modeling and simulation of PCM-wall for the occupancy profiles considered yields maximum energy heating savings of the order of 10 kWh, while the inversion temperature of PCM is kept at 19 °C. However, the ventilation scheme implemented with occupancy profile has affected the energy savings potential of PCM-wall in the building envelope during heating. Selection of optimal fusion temperature of PCM needs careful attention for enhancing the energy efficiency of the PCM-wall. The analysis done has not been experimentally validated and expected to be in the preliminary stage yet. Further in-depth research is required for its effectual incorporation in actual building envelope.

In modern era, with the advancement in building simulation methodologies it is now possible for engineers to predict and assess the building thermal response for any change occurring in the heat load demand (both on-peak and off-peak load). In this spectrum, a new method to ascertain the effects of PCM envelope towards improving the thermal comfort in indoor spaces and its associated energy consumption was presented by Kuznik et al. [107]. They have used TRNSYS simulation tool and developed TRNSYS Type 260 for their analysis. The numerical model analysis performed was found to match with experimental data but with minor discrepancies. Notwithstanding of this agreement related to heat capacity, internal air temperature and inside surface temperature of cell vertical wallboards it is of prime importance that to identify the exact convective heat transfer coefficient. This would help to predict the micro-level heat interactions that occur in PCM nodules during phase transformation processes.

Interesting case studies on a passive solar building architecture and a naturally ventilated passive solar building with two direct heat gain rooms using isothermal phase change material were done by Heim [108]. First case study focuses on the solar building that contains predominant glazing structures that allows for more incident infrared radiation inside the building for space heating. Second case study concentrates on the triple zone of a naturally ventilated building. Except on floor surface, all inner walls on the east and west sides of solar glazed building were provided with gypsum–PCM composite wallboard lining. The southern external wall of naturally ventilated building was provided with transparent insulation material (TIM) that separates the two passive rooms on the east and west sides of the building. Fusion temperatures of 21, 24, 27, 30 °C and 20, 30, 40 °C were designated for the gypsum–PCM composites and TIM–PCM respectively in this analysis. Numerical simulations were conducted for the two buildings according to the effective heat capacity method (EHCM) and additional heat source method (AHSM).

The outcome of first case study suggests that for varying climatic conditions throughout the year only two gypsum–PCM composites having melting temperature of 21 °C perform better than the other PCM composites. It stores more latent heat during summer and releases the stored heat in winter to offset heating load demand. Likewise, in the second case study it is found that the TIM–PCM set to its melting point of 20 °C shows good performance than with other melting set points and also ensured stable thermal conditions in indoor space of the building. The thick and thin configurations of PCMs installed in both buildings respectively has augmented the latent heat storage and release capacities as well as the excess heat energy stored could be utilized during night time.

One step further to improve the thermal comfort conditions inside the occupied spaces and to minimize the inclusion of PCM in the building thermal mass, Karlessi et al. [44] and Santamouris et al. [109] conducted experiments on various color coatings suitable for passive building cooling applications. They analyzed the thermal performance of infrared reflective cool coatings for buildings wherein organic paraffin PCMs that is combined with a suitable binding system was used and subsequently doped it with the cool coating suspensions. The organic paraffin PCMs developed contains microencapsulated pigments of 17–20 μm particle size and has latent heat of fusion around 180 J/g. The organic PCMs were prepared for three different melting temperatures of 18, 24 and 28 °C at different concentrations and been performance tested in coatings of six different colors. The PCM-doped color coatings applied on to the building exterior has reduced its surface temperature to almost 7–8 °C while compared to the common and simple cool color coatings. Furthermore, it is observed that the surface temperature reduction was about 12% than the common color coatings of the same color. By this, acceptable levels of indoor thermal comfort conditions with reduced indoor temperature fluctuations have been accomplished. Table 4 refers to the maximum surface temperature and surface temperature differences for various color coating samples.

Table 4
Max surface temperature and temperature differences of various color coating samples (°C) [109].

	Black	Blue	Green	Grey	Brown	Golden brown
T_{max}						
Common	67.9	63.1	64.7	65.2	62.6	58.1
Cool	62.2	58.6	61.5	62.3	60.1	56.1
PCM	60.5	57.0	59.8	60.9	58.5	55.0
ΔT common-PCM						
Common	–	–	–	–	–	–
Cool	5.7	4.4	3.2	2.9	2.5	2.0
PCM	7.4	6.1	4.69	4.3	4.1	3.1
ΔT cool-PCM						
Common	–	–	–	–	–	–
Cool	–	–	–	–	–	–
PCM	1.8	1.7	1.6	1.4	1.6	1.1

Striding on to the next option of achieving passive cooling in buildings, Shanmuga Sundaram et al. [110] demonstrated the significance of using PCM and two-phase gravity assisted thermosyphons (TPCT) systems for telecom shelter buildings subjected to the tropical and desert conditions. Commercially available hydrate salt HS 29 which has its melting point in the range of 28–30 °C, heat of fusion of 205 kJ/kg and specific heat of 1440 kJ/kg K was employed as the PCM. Thermal performance of this passive cooling system was tested for cooling and heating seasons.

It is noted that, thermosyphon system acts like a thermal diode during charging time of PCM in morning hours, wherein the heat emitted by telecom equipments are captured and stored in the PCM system. Because of the significant temperature gradient that exists between the ambient and the thermosyphon system during night hours, the stored heat energy from the PCM enclosure tank has been retrieved and exhausted to the ambient effectively. In addition, the authors suggest that by incorporating this passive cooling system instead of conventional A/C system which would consume 22,776 kWh of energy, approximately 14 tonnes of carbon foot print could be conserved on a yearly basis. This would also help to elevate the present status of these telecom shelters into the spectrum of green buildings.

The cute opportunity available for enabling passive design in buildings would call for the free cooling concept. In here, the cold energy contained by the ambient air in night time acts as an ingredient for charging the LHES system whilst utilizing the same fresh air for meeting out the cooling and ventilation requirements in indoor spaces effectively. The stored cold energy will eventually be discharged from the LHES system in order to cater the peak cooling load demand in day hours. The ambient air with its temperature below or near to the requisite melting temperature of PCM would generally be used for charging the PCM. During day-peak hour load conditions passing the indoor air over the charged PCM enables it to transfer and release the cold energy to the recirculating air thereby; it gradually brings down the air temperature to the indoor comfort temperature level.

In this regard, Arkar and Medved [111] integrated the temperature-response model of packed bed LHES system with building thermal response model using Fourier series and TRNSYS software for predicting the indoor temperature and accurate size of LHES system for free cooling applications. Paraffin-based RT 20 PCM enclosed in spherical modules was accounted in this study and they were analyzed using the cylindrical LHES system. The developed models were numerically simulated for different types of natural ventilation and free cooling modes. The numerical solutions thus obtained were compared with the experimental measurements for

inlet boundary conditions typically used for free cooling processes and they are subsequently validated.

It is realized that for the test building considered, RT 20 PCM with its peak temperature in the range of 20–22 °C exhibited better thermal performance. Based on this the optimum size of encapsulated PCMs with aspect ratio (LHES length to diameter ratio) for heat storage was expected to be 25 mm and 1.5 respectively. Also, the net weight of PCM per sq. m of floor area was determined to be 6.4 kg and this value is found optimum for experiencing improved free cooling effects in the case study building. Overall, this system can be regarded as energy efficient for and suitable for its integration in low energy buildings. Similar approach on estimating the free cooling potential of LHES system was executed by Medved and Arkar [112] wherein they used the same RT 20 PCM as heat storage medium. Six cities in Europe with different climatic conditions were selected for the analysis. Numerical simulation performed was able to predict and optimize the PCM transition temperature with its range and the ratio of PCM mass to the air volume flow rate for the changing temperature profile in indoor space of selected building. RT 20 PCM which has a good rife in fusion temperature range of 12 K shows enhanced performance in all the climatic regions being considered. Moreover, the LHES system was sized to an optimal value in the range of 1–1.5 kg of PCM per m^3/h of primary ventilation air for free cooling applications.

Besides getting energy savings from ceiling mounted free cooling LHES systems, underfloor air distribution systems are being preferred nowadays to cater thermal load demand as well as to provide comfort conditions in indoor spaces. In view of improvising the energy efficiency and usage of cooling utilities in buildings, Zukowski [113] described the combined effects of short-term LHES system with underfloor air distribution system for cooling application in buildings. Heat storage material (PCM) was enclosed in a new type of polyethylene film bag enclosure for ensuring effective heat transfer during phase change processes. The pictorial representation of the PCM enclosure, its arrangement and the particular stages of solidification and melting processes are depicted in Fig. 16.

Paraffin wax based RII-56 was the PCM used for experimentation. Different set of experiments were performed on this system by varying the inlet air temperature and volume flow rate of inlet air from 60 to 70 °C and 20–40 m^3/h. Enthalpy of fusion for this PCM was determined to range from 240 to 262 kJ/kg with high thermal capacity being observed between 49 and 57 °C. This PCM contained in the polyethylene film bag show minimum thermal stresses and resistance during charging and discharging processes and acts as a potential candidate for enabling free cooling in buildings. Despite having various types of PCMs for heat storage, shape stabilized PCM (SSPCM) a new kind of compound consisting of PCM as dispersed phase and high density polyethylene (HDPE) or similar materials as supporting material is of greater interest, in recent years. The exciting feature of SSPCM is that so long as the operating temperature is below the melting point of supporting material, SSPCM would not alter its shape and reduces the risks related to leakage. SSPCMs can be used for thermal energy storage in buildings without the necessity for encapsulation.

In this connection, Lin et al. [114] studied the thermal storage performance of SSPCM plates for an underfloor electric heating system that is equipped with ductless air supply arrangement. The SSPCM plate system coupled with underfloor heating system results in an increase of average indoor peak temperature by 8 °C with SSPCM surface temperature maintained at 45 °C all the time. This eventually shifted the on-peak total electrical energy consumption to off-peak periods. By varying the air supply rate in different conditions and with proper melting temperature of SSPCM plates being selected based on heating load demand the indoor temperature can be set to the comfortable range.

Zhou et al. [115] has numerically verified an air conditioned office building that is integrated with SSPCM plates for estimating the cool storage and free cooling potential using an enthalpy model. SSPCM plates were assumed to be fixed to the interior of buildings for capturing heat energy in night time and to release the stored energy while demand arises during daytime. By installing the SSPCM plates it is suggested that air change per hour (ACPH) required during daytime was only 1/h and the remaining cooling load demand is catered by the SSPCM energy storage module. This also maintains the indoor temperature well below 28 °C during daytime. A key observation made on this SSPCM plates was that it could reduce about 76% of day energy consumption while compared to the conventional cooling system that is not coupled with SSPCM plates and night ventilation. The electrical coefficient of performance (COP) of supply air fan with and without SSPCM plates during night time was expected to achieve 6.5 and 7.5 respectively. This hybrid system is able to find its potential application in modern buildings and could make them energy efficient. Halawa and Saman [116] discussed the effects of different parameters on the LHES system performance through numerical simulation based on the model inputs from earlier research studies conducted by various researchers. In this study the thermal performance of phase change flat slab heat storage system was investigated. Observations related to melting and freezing characteristics based on the temperature gradient, mass flow rate, thickness of slabs, air gap between slabs, mass and surface area of PCM, geometric parameters of PCM and heat transfer interactions between PCM and heat transfer fluid were reported.

Authors have explicated two temperature differences that are most essential parametric quantities which signify the rate of heat transfer during charging and retrieving heat energy from the LHES system. If the temperature differences are higher during melting/freezing the rate of heat exchange would also be higher. This parametric evaluation is helpful in understanding the heat transfer rate during phase change processes where natural convection effects could not be established accurately.

Butala and Stritih [117] experimentally determined the cold storage capacity of PCM especially applicable for free cooling applications in buildings. They used paraffin-based RT 20 PCM which possess latent heat of fusion of 172 kJ/kg with melting point of 22 °C. Two aluminum fins were provided on either sides of the metal box enclosure which in turn would enhance the heat transfer capacity of cold storage. Detailed investigation was performed on the selected PCM by varying the inlet air temperature and velocity during night time. For air velocities of 1.5 and 2.4 m/s and inlet air temperature to the cold storage unit of 26, 36 and 40 °C the cold energy that was stored during night time ranged from 340 to 950 kJ over a period of 6 h. Using the derived mathematical relations the cold energy storage potential of the PCM was properly estimated for varying conditions of air velocities and inlet air temperature. Fig. 17 shows the cold storage system with fins dimensions. Similar research works in context with the implementation of free cooling principle/night ventilation for LHES system to reduce daytime peak cooling load demand and indoor temperature fluctuations have been presented [118,119]. Embedded heat pipes in PCM cold storage unit assists in augmenting the actual heat transfer mechanism between the cold air and the PCM. Altogether, the effectiveness of cold storage unit mainly depends on the range of daily temperature fluctuations but not on the average temperature distribution. In addition, the heat pipe provisions introduced in PCM to cool the indoor environment would reduce the number of LHES system requirements vividly.

Lazaro et al. [120] proposed an empirical model based on experimental outputs pertaining to real time conditions for a PCM-air heat exchanger which is capable of handling the cooling load demand in day hours of the building through free cooling concept.

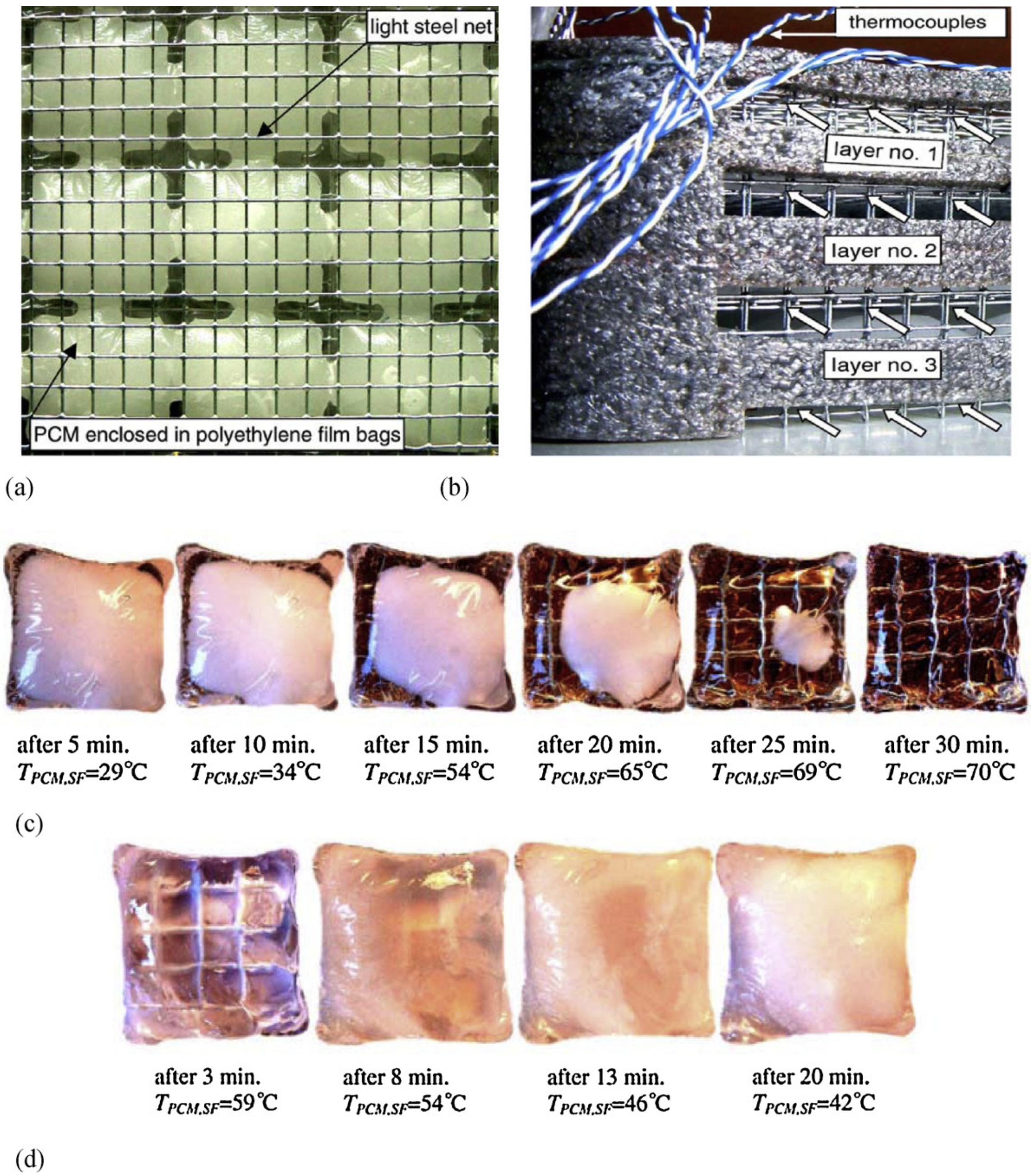


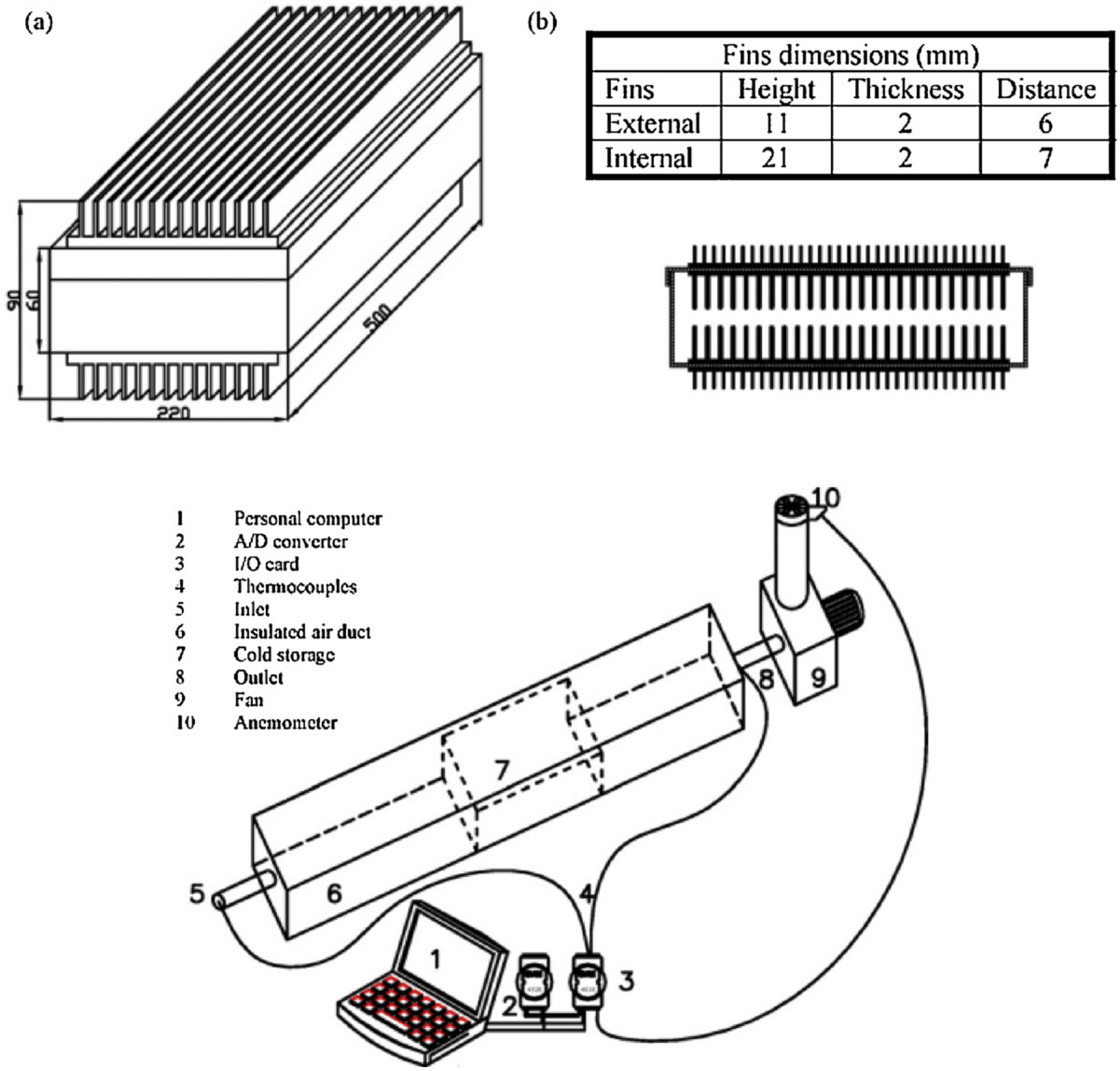
Fig. 16. (a) PCM contained in the polyethylene film bag; (b) arrangement of PCM layers; (c) particular stages of melting process; (d) particular stages of solidification process [113].

The transient response of the PCM-air heat exchanger was studied using two prototype systems wherein prototype 1 comprised of inorganic PCM and prototype 2 was provided with organic PCM. Model analysis indicates that for maintaining constant or specific temperature level in indoor spaces PCM inversion temperature must be either lower enough to cater the cooling load demand or has to be in the proximity level to the indoor set temperature.

The choice of PCM remains to be a vital factor to examine the thermal response of heat exchanger to transient operating conditions. Power or load demand should be included while evaluating the phase change and heat exchange mechanisms involved between the PCM and the air heat exchanger at constant temperature. This in turn would facilitate for developing such heat exchangers for other applications that requires constant temperature for effective heat transfer operations.

Flow and heat transfer characteristics of fluid flowing through the modular heat exchanger equipped with PCM-heat storage element that can be used for free cooling application in buildings was established by Antony Aroul Raj and Velraj [121]. The PCM-heat storage module was modeled under GAMBIT environment. CFD analysis using FLUENT software was performed to investigate and visualize the heat transfer interactions between the flowing fluid and PCM module. The photographic view of the circular PCM-heat storage module and its isometric view are presented in Fig. 18.

The transient analysis includes the input parameters such as inlet air temperature at 295 K, inlet frontal velocity of 0.7 m/s and initial temperature at 305 K. Based on the CFD results and successive experimental validation, it is summarized that: in order to closely match the transition temperature of PCM for both theoretical and experimental analysis, the scanning rate done on PCM



Fins dimensions (mm)			
Fins	Height	Thickness	Distance
External	11	2	6
Internal	21	2	7

Fig. 17. (a) Shape of cold storage, (b) cross-sectional details and fins dimensions (c) experimental set up of cold storage [117].

using the differential scanning calorimetry (DSC) must be based on the cooling/heating rate for the selected application; air spacers introduced in the PCM module enhances the rate of heat transfer and retention time of air; increase in the surface heat transfer coefficient has reduced freezing capability of PCM significantly for frontal velocity of 2 m/s, whereas at higher velocities of air this effect is seen to be reduced that can be attributed to the resistance of PCM; phase change is not complete near the outer wall of the module which can be improved by design modifications taking into account of varying resistance exhibited by the PCM module.

Based on these research studies that have been reviewed it can be inferred that on an average the passively designed buildings integrated with LHES systems can collectively contribute for achieving 10–15% reduction in space conditioning loads. They would also reduce the temperature swings inside the occupied spaces thereby; maintain the indoor temperature at or near

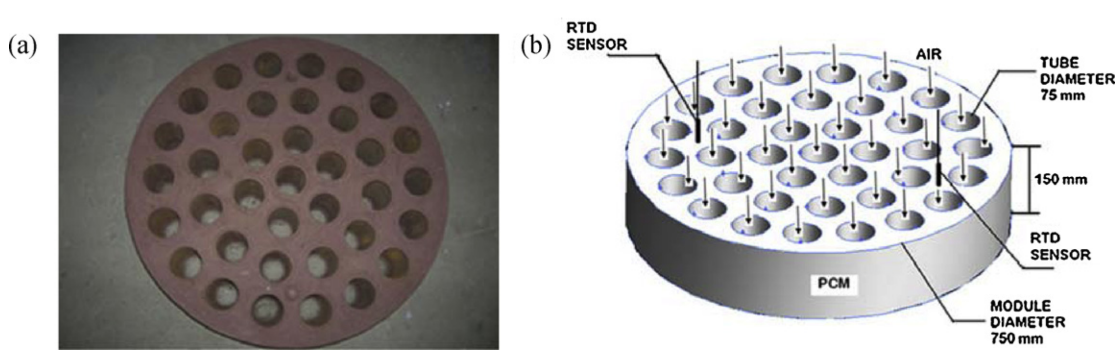


Fig. 18. (a) PCM-heat storage module; (b) isometric view of PCM module [121].

comfortable conditions and would contribute to enhance the energy efficiency of buildings.

4.2. Active systems

A much improved way of storing heat energy in buildings can be made possible by using active LHES systems. Buildings designed for accommodating active thermal energy storage systems can be made energy efficient as well as high degree of control of the indoor conditions can be accomplished. Basically, LTES systems of this type comprises of supplementary mechanical systems to enhance the heat storage capability of the system.

Active LHES systems installed in buildings would shift thermal load from on-peak to off-peak conditions thereby; conserve overall primary energy that is being spent on cooling or heating in buildings. In this section the application potential of active LHES systems in buildings is focused through detailed review of many interesting research studies and the outcome of these studies are presented for discussion. Operating modes of LHES system is briefly described in Table 5 which gives better understanding of its functional aspects.

Direct heating in buildings using conventional electric heaters, radiators or heat pump utilities would impose high degree of electrical energy consumption especially during peak load hours. By incorporating LHES system with these utilities can supplement the heat load requirements and would possibly conserve energy. Considering these aspects, Hamada and Fukai [122] conducted a research work on LHES system integrated to a heat pump unit primarily meant for providing air conditioning in buildings. They concentrated only on the heating mode wherein the exhaust heat from the heat pump was used to charge the PCM contained in the LHES tanks for supplementing daytime heating in buildings.

LHES tanks were fabricated with carbon-fiber brushes, heat exchanger network and paraffin wax PCM enclosure. Numerical analysis was done on the LHES tanks and the simulation results are compared with experimentally determined values. The outcome of this study infers that by selecting proper diameter and volume fraction of fibers in brush to 80 mm and 0.008 respectively would contribute for improvement in thermal storage of PCM during discharging and charging processes. The addition of carbon brushes on the LHES tanks also helps to reduce space requirements and cost by 75% as well while compared to tanks without brushes. There is a possible limitation observed in this type of storage tanks in terms of storage capacity and heat transfer rate while applied to practical situations. A recent research study reported by Agyenim and Hewitt [123] describes the development of finned PCM-heat storage system for space heating in residential building located in UK, thereby; reducing the heat pump operational cost considerably. They used paraffin RT58 as the PCM and enclosed it in a 1.2 m long horizontal tube shell with 3 mm thickness.

In order to improve the thermal conductivity of RT58 PCM and experience better heat transfer characteristics, copper tube of 65 mm encompassed with 8 long fins of size $1100 \times 120 \times 1$ mm (length $\times$ width $\times$ thickness) were provided and placed in the center of the tube shell. Experimentation on melting and freezing processes of PCM were performed for different thermal cycles on the basis of economy 7 tarrif for the building. It is seen that RT58 PCM without having heat enhancement elements could cater only 52% of maximum heating energy. On the other hand, same RT58 being while provided with longitudinal fins arrangement exhibited good charging and discharging characteristics and reduced the storage tank size by 30% without compromising on the heating demand. This indicates that heat storage systems infused with PCM would support and supplement the heating demand in buildings and improve the life cycle of heat pumps that is intended for heating applications.

From the stance of getting more information on active LHES systems for energy efficient buildings it is seen that many research studies have been focused on cool thermal energy storage (CTES) technologies for building cooling and A/C purposes than for heating applications. In recent years, development of potential CTES systems using chilled water, ice storage and other type of PCMs has shown greater impetus in shifting peak load demand to off-peak conditions, which can be regarded as part of energy management plan for efficient buildings. Depending on the type of combinations of cool storage media, charging and discharging processes CTES systems are broadly classified into chilled water, ice, eutectic salt and PCM storage options. Ice storage is further categorized into ice slurry, ice-on-coil (external or internal melt) and ice harvesting systems. Charging and discharging mechanisms for ice storage systems may be accomplished by means of separate refrigerant loop or with brine solution. Referring to Table 5, CTES systems can be designed based on full or partial storage schemes.

A full CTES system meets out on-peak load demand entirely from storage itself. Partial CTES system caters cooling load demand partly from storage and the remaining from the chiller plant. Chilled water based CTES systems operate on the sensible heat capacity of water and temperature gradient between the supply and return water network interfaced with the building load. In the class of CTES, PCM based energy storage systems are now preferred in buildings because of its enhanced thermal performance and other benefits. Table 6 gives out information on some of the essential aspects of CTES and LHES systems.

Chen et al. [124] demonstrated a method of determining the thermal performance and pressure drop of encapsulated LHES tank in charging cycle by using water with nucleating agents as PCM for enabling effective cooling in buildings. The key parameters including size of encapsulation/PCM capsules, HTF flow rate, HTF temperature and concentration of nucleating additives that influence the thermal performance of the CTES system were experimentally determined. In particular, complete storage of cool energy was quite possible while the inlet temperature of HTF was maintained below 100% probability of crystallization of PCM. On the contrary, by increasing the flow rate and lowering the temperature of coolant (HTF) the charging rate of PCM was enhanced but there was some increase in the pressure drop that occurs across the LHES tank due to coolant flow conditions. Empirical correlation was developed to calculate the coolant pressure drop which occurred during charging of PCM. Transient response of PCM-air heat exchangers dedicated for acquiring air conditioning in buildings was numerically simulated and experimentally validated by Dolado et al. [125]. The charging and discharging characteristics of PCM-air heat exchanger in single plate and entire TES unit schemes were evaluated. Models developed were based on previously reported research studies done by the authors. Accuracy of the models was verified with the experimental values presented in [49]. The macroencapsulated organic based PCM embedded in aluminum rigid slabs weighs 135 kg approximately and are located in parallel to the airflow direction in the storage module. Schematic representation of the experimental set up, pictorial view and the 3D sketch of the compact organic PCM storage module are shown in Fig. 19.

It is seen that by modifying the enthalpy value and phase change temperature of this PCM results in an increase in solidification and melting time by 10–11%. This phenomenon has influenced the heat transfer characteristics of PCM in charging and discharging cycles and show relative effects on enthalpy-temperature values of PCM. Since air was used as the HTF the thermal performance of the PCM-air heat exchanger was comparatively lesser than the other CTES systems. Solving the numerical models using TRNSYS building simulation tool for 1 h time steps with calculation-loop intervals of

Table 5
Modes of operation of active LHES system.

Mode of operation	Cooling cycle	Heating cycle	Presence of heat transfer fluid (HTF)	Type of storage
Charging process	Cooling of storage system by means of separate cooling unit in order to remove heat from the storage	Supplying heat to the storage system using separate heating unit	Yes	Full storage
Simultaneous charging process and thermal load balancing	Cooling of storage system by means of separate cooling unit in order to remove heat from the storage and offsetting cooling load from building directly	Providing necessary heat to the storage system using separate heating unit as well as catering heating load in buildings directly	Yes	Partial storage (either for load leveling or demand limiting operation)
Discharging process	Meeting out cooling load demand entirely using stored cold energy from storage system only	Operating only the storage system to completely retrieve heating load demand	Yes	Full storage
Instantaneous discharging process and thermal load balancing	Sharing of cooling load demand by retrieving stored cold energy from storage system and operating cooling unit in parallel cycles	Retrieving heat load demand by activating storage system and heating unit in combined manner	Yes	Partial storage (either for load leveling or demand limiting operation)

5 min or less the accuracy of the results obtained could be maximized.

Thermal response and heat transfer interactions of CTES system using technical grade paraffin wax Rubitherm RT5 PCM was studied by He and Setterwall [126]. Experimentation was done by static and dynamic storage processes wherein in dynamic process chilled water around 4–6 °C was sprinkled onto the samples of PCM to measure the freezing rate. Based on the results the freezing point and latent heat of fusion of RT5 PCM is found to be 7 °C and 158.3 kJ/kg respectively. This PCM exhibited better thermophysical, thermodynamic and heat transfer characteristics in its segment. The volumetric contraction during phase change from liquid to solid is noted to be 6.32%. All these features help RT5 PCM to be a cost effective and potential candidate for low temperature CTES application for buildings. Modeling and simulation of thermal characteristics and performance evaluation of packed bed CTES systems have been established in recent times [127,128]. These studies give explicit information on the parameters to be considered for modeling CTES systems. Results of these works help to understand the heat transfer mechanism and thermal response of PCMs subjected transient load conditions in during solidification and melting processes.

Pare and Bilodeau [129] examined the performance of chilled water based LHES system integrated in a building to facilitate the cooling and air conditioning requirements. They have implemented the concept of blending LHES and free cooling for maximizing the energy efficiency of the building considered. Experimental measurements observed in the building site indicate that: per day energy consumption is reduced from 16,706 to 15,572 kWh, average cooling production is increased from 2744 to 5501 kW, average total production is improved by 8824 kW from 5117 kW, cooling production efficiency with and without free cooling is expected to achieve 0.259 and 0.415 kW/tons respectively. This study is helpful in understanding the significance of installing CTES systems in real time building cooling and air conditioning applications in order to enhance energy efficiency to the maximum possible extent.

Martin et al. [130] developed a novel CTES system that is suitable for storing cold energy by direct-contact PCM–water interface and helps to shave peak cooling load demand. Paraffin-based PCM was used as thermal storage medium with melting point at 7 °C and storage density of 156 kJ/kg. In here, phase separation between the PCM and the HTF was made possible through density difference existing between the two components. Experimental set up and the sequence of charging process of this CTES system are depicted in Fig. 20. Power required for charging and discharging the PCM ranged from 30 to 80 kW/m^3 and the energy storage and release rate was found appreciable. This system has some practical limitations in terms of PCM containment, non-uniform channeling, mass flow rate of HTF, thermal cycling and repeatability of PCM. Authors have suggested for carrying out in-depth study on the droplet size to be in precision with the available empirical relations in order to improve the thermal performance of this system further.

Table 6
Essential aspects of active CTES and LTES systems [54,153].

	Chilled water storage	Ice storage	Eutectic salt storage	PCM storage
Specific heat (kJ/kg K)	4.19	2.04	–	2–4.2
Latent heat of fusion (kJ/kg)	–	333	80–250	130–386
Heating capacity	Low	High	Medium	Medium
Type of chiller	Standard water	Low temperature secondary coolant	Standard water	Standard water
Volume of storage tank (m^3/kWh)	0.089–0.169	0.019–0.023	0.048	–
Storage charging temperature (°C)	4–6	−6 to −3	4–6	−10 to 6
Storage discharging temperature (°C) (higher than charging temperature)	1–4	1–3	9–10	5–8
Ratio of cooling capacity	20–30	More than 50	15–40	20–50
Performance coefficient of chiller	5.9–5	4.1–2.9	5.9–5	5.9–5
Fluid for discharging storage	Standard water	Secondary coolant/brine solution	Standard water	Standard water
Tank interface	Open system	Closed system	Open system	Closed system
Space requirements	More	Less	Less	Less
Flexibility	Existing chiller usage; fire protection duty	Modular tanks suitable for small/large installations	Existing chiller usage	Existing chiller usage
Maintenance	High	Medium	Medium	Medium

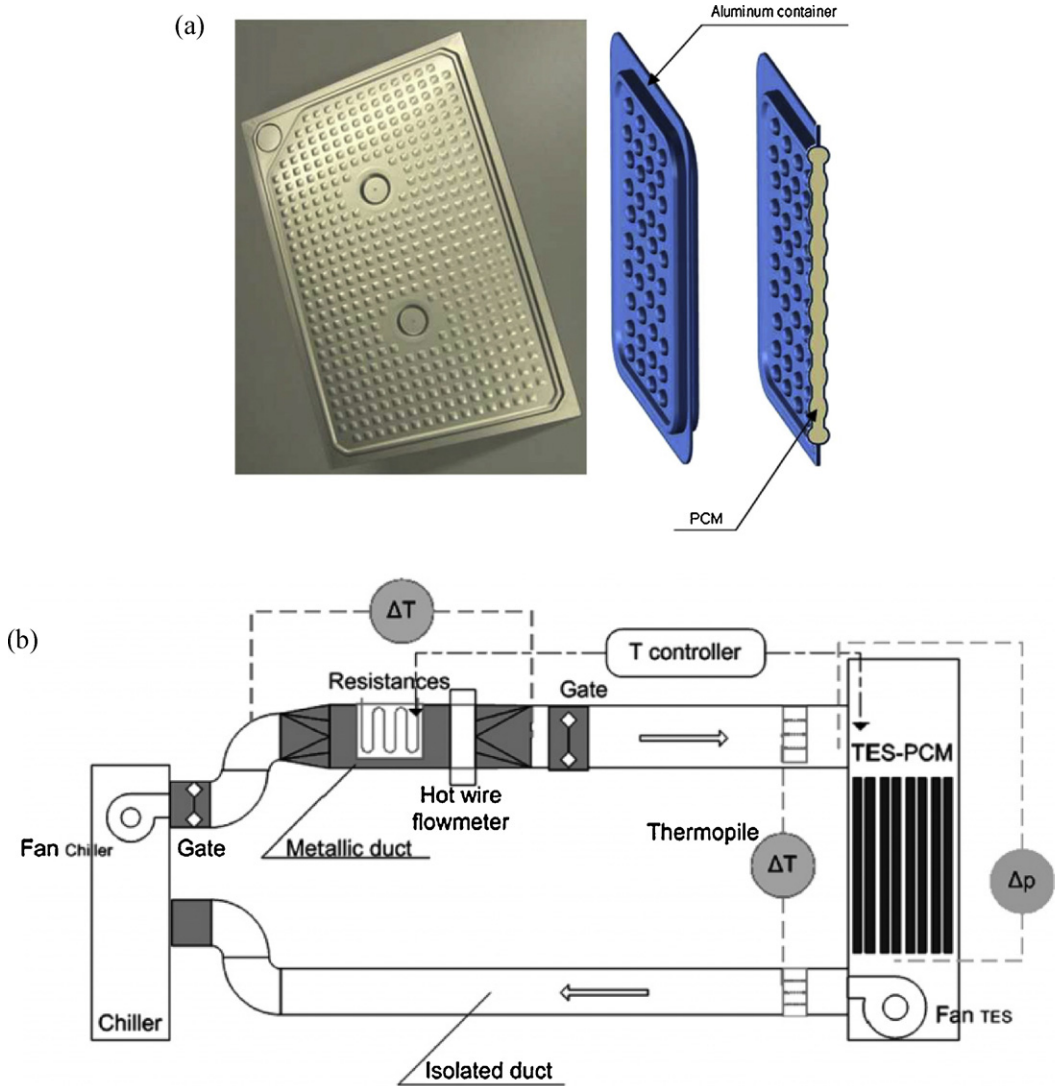


Fig. 19. (a) Photographic view of macroencapsulated organic PCM enclosed by aluminum slabs; (b) experimental set up of PCM-air heat exchanger [125].

The significance of exergetic and energetic analyses of shell-and-tube type LHES system dedicated for providing cooling in the University building located in Turkey was assessed by Ezan et al. [131]. The energy and exergetic efficiencies of this PCM-heat exchanger were evaluated using process influential parameters during solidification and melting phase change processes. The PCM-heat exchanger designed and fabricated using copper, steel and PE32 tube materials were tested under two varying shell diameters of 114 and 190 mm. The flow rate and inlet temperature of HTF in charging mode of PCM were varied by 2, 4 and 8 l/min and −5, −10 and −15 °C respectively. Conclusions derived for charging and discharging schemes of PCM-heat exchanger indicates that: for any increase in the inlet temperature and flow rate of HTF the energetic efficiencies of PCM gets decreased during charging mode and increased while undergoing discharging process.

Likewise, the exergetic efficiency increases for the aforementioned process conditions and that the inlet temperature of HTF was responsible for the rise in the exergetic efficiency. Due to the gradient of PCM fusion temperature and inlet temperature of HTF during melting process, irreversibility tends to increase which in turn augmented the exergetic efficiency. Increase in the shell diameter also has an impetus on the exergetic efficiency. Collectively, this analyzes presents a viable means for developing efficient LHES-heat exchangers for building cooling applications. Kalaiselvam et al. [132] demonstrated the finned encapsulation technique on spherical and cylindrical PCM configurations of LHES system for catering building cooling load requirements. The charging rate of PCMs encapsulated in cylindrical configuration is reduced by 47% than the spherical configuration. For the same volume of PCM considered, by introducing slotted fins arrangement cylindrical encapsulation yielded 72.27% reduction in solidification time and 51% less melting time than the spherical encapsulation with same configuration. Numerical solutions obtained in this study also well agreed with the experimental measurements.

Other form of storing cold energy can be actively accomplished with the use of ice storage systems. In ice storage systems latent heat of fusion of water is used to store cooling energy. Ice may be produced by circulating low temperature HTF (brine solution or glycol) available in the range of −3 to −8 °C into the ice banks (tanks). Ice storage systems are generally categorized into internal melt ice-on-coil, external melt ice-on-coil, ice slurry, ice harvesting and encapsulated ice systems. Encapsulated ice storage systems are now gaining its momentum in modern building air conditioning applications.

Erek and Ezan [133] explicated the charging process in an external melt LHES system through performing a numerical and experimental methodology wherein a small section of the LHES tank with a set of symmetry assumptions were considered, which

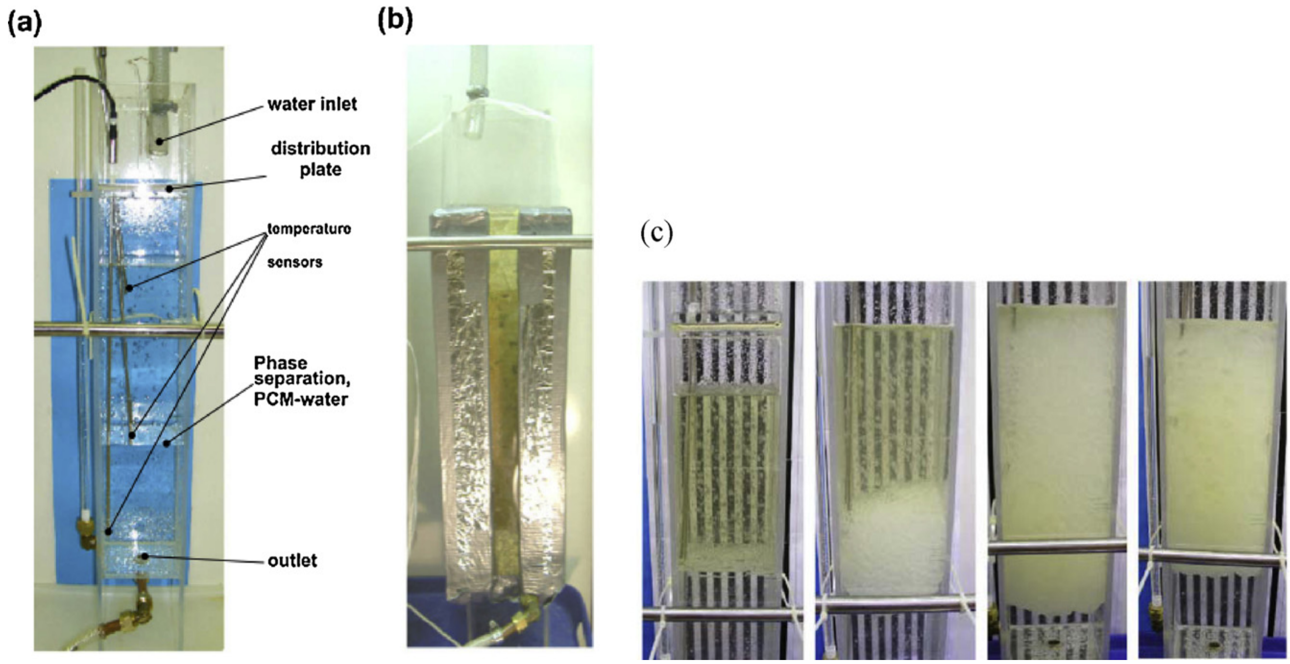


Fig. 20. (a) Experimental set up – uninsulated porous-bed formation; (b) experimental set up – charging and discharging process examination; (c) charging of direct-contact CTES system [130].

in turn reduced the complexity involved in the numerical simulation. Control volume approach adopted in numerical analysis helps to predict and obtain appreciable results related to system dynamics and HTF flow characteristics to determine the cool storage capabilities of the LHES tank. Energy storage capacity of the present system increases with a rise in the flow rate of HTF and the inlet temperature of HTF governs the heat storage efficiency of PCM than volumetric flow rate of HTF. This fact was very well encountered in the recent study as explained above in [131]. Specifically, the inlet temperature of HTF plays a major role in deciding the thermal performance of LHES systems on a long run. The efficacy of ice thermal storage system which would bring in peak load shaving and reduce energy consumption in buildings has been proposed by Yau and Lee [134]. This field study contemplated the application of ice slurry CTES system for a University building situated in the tropical region of Malaya. Ice slurry CTES system simulated in TRNSYS for full storage, partial storage with load leveling and demand limiting schemes produced greater cost-energy savings for electricity usage. Of which the full storage method yields 24% of electricity cost-energy savings. Similarly, cost savings from peak power demand also arises wherein full storage mode conserved 60%, partial storage with demand limiting and load leveling methodologies results in 37% and 25% respectively.

Humidity level in indoor spaces was maintained at the design values for full as well as partial storage CTES systems. Limiting factor of this ice slurry CTES system was its overall energy consumption in freezing the ice by which it gets increased by 20% while compared to the conventional system in operation in the building. But, the CTES system was capable enough to handle peak load demand and shifted 585 and 295 MJ/h from the baseline design cooling load of 1207 MJ/h through partial load leveling and demand limiting storage techniques respectively. Furthermore, the cooling effect felt inside the conditioned space was more which dictates to design air handling unit (AHU) for lower capacities. Replacement of the conventional cooling system with the new ice slurry CTES system can work for appreciable cost-energy savings in modern buildings located in tropical regions.

Yang and Yeh [135] worked on to revamp an ice storage system in an aquarium building for improving its overall operational performance with less power consumption to produce ice for cooling purposes. Evaporator of conventional chiller has been replaced with a water tank having plastic tubes embedded in it as shown in Fig. 21. HTF (brine solution) flows through these tubes around −7 °C and produce the required quantity of ice in the tank to meet out the on-peak thermal load demand. The annual energy audit conducted on this CTES system concludes that on an average 300 tons of refrigeration (RT) was additionally available from this system which could be used to cater the cooling load demand effectively. Shifting of on-peak load to off-peak periods was also possible with this system which was justified by 25% in summer, 50% in spring and fall seasons and 100% during winter. In total, the system functions at 80% of its full load capacity thereby; enabling increased thermal performance and cost effectiveness without sacrificing energy efficiency.

Erek and Dincer [136] pointed out that the heat exchange mechanism of encapsulated ice thermal storage system is not constant but varies across downstream line of HTF flow. They identified that the rate of solidification and melting was greatly influenced by the changing nature of heat transfer coefficient around each capsule and with the temperature of HTF. Decrease of inlet temperature of HTF and increase in the Reynolds number has led to an increase in the heat transfer rate between the ice capsules and HTF. In particular, the solidification of ice was largely governed by the magnitude of Stefan number, capsule diameter and capsule arrangement (row number). Hence, while designing the encapsulated ice thermal storage systems these factors must be considered for getting enhanced heat transfer characteristics and thermal efficiency.

Inline to the ice thermal energy storage system simulation, MacPhee and Dincer [137] performed a detailed investigation on the energetic and exergetic efficiencies of four different ice thermal energy storage systems suitable for air conditioning applications. They analyzed the charging, storage and discharge cycle efficiencies for the ice slurry systems, ice-on-coil systems (external and internal melt) and encapsulated ice storage system separately as case studies. The variables used in the case studies

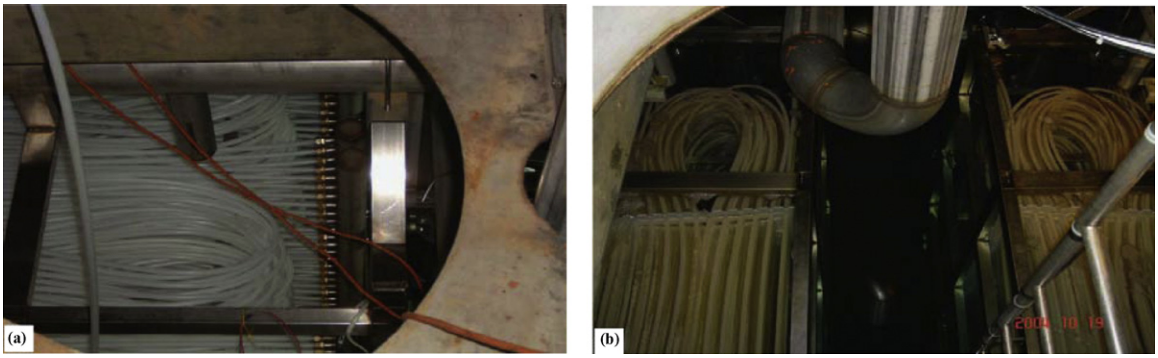


Fig. 21. (a) Embedded tubes made of plastic for converting ice storage into a total-freeze-up system, (b) completed total-freeze-up ice storage tank on the site building [135].

and information pertaining to these systems were referred from Wang and Kusumoto [264] and Dorgan and Ellison [265] respectively. As a result of the analyses the energetic efficiencies of these systems operated under full storage mode yields 99% in charging and discharging cycles. This value tends to dictate that the system may reach ideal conditions but in practice, due to the generation of entropy and other inherent losses this value may be lowered and would be apparent to the exergetic efficiency. Likewise, the exergetic efficiencies ranged between 46% and 76% during charging process and 18% and 24% in discharging process. In partial storage load shifting operation the parametric values obtained were very close to that of full storage operation and the deviation found was attributed to the heat leakage in partial storage method. It is also suggested that ice slurry and ice-on-coil systems are considered to be most energy and exergy efficient systems respectively with 14.05% of total exergy efficiency found in the latter system.

Optimization of ice-CTES systems on the basis of peak load shaving performance, charging and discharging characteristics, thermal efficiency and minimal life cycle cost have been described in these studies [138–141]. Through performing intense computer simulations on CTES systems for the aforesaid criterion the optimal chiller capacity, ice storage densities, peak electricity consumption and power demand has been obtained. In short, the optimization of CTES systems suggest that about 55–60% of electricity cost-energy could be saved each month in buildings and making them energy efficient. Some guidelines were also presented in these works for prioritizing chiller operation and control strategies to be followed during charging and discharging processes for the full and partial CTES methodologies.

Ice thermal energy storage system incorporated with AC system in a clinic building in Kuwait was examined by Sebzali and Rubini [142]. The CTES-A/C system operated under full, partial load leveling and partial demand limiting storage strategies for selected charging and discharging cycles contributed for reduction in electrical energy consumption and shifted peak load demand in the building. Of which, CTES-A/C system with full storage scheme performed better than the rest and reveal more energy storage and release capacities.

Hasnain and Alabbadi [143] discussed the application potential of coupling ice thermal and chilled water energy storage systems with air conditioning systems and found them feasible by having reduced electrical energy consumption and peak load shaving significantly in Saudi Arabia. Peak cooling load and peak electrical energy demands were expected to be reduced by 30–40% and 10–20% respectively. This actually privileged the installation of CTES in buildings located in this region. Cost-energy savings and overall maintenance cost involved on these CTES systems are economical, thus making these systems viable for Saudi Arabian buildings. Authors in their another study explained the integration of partial storage CTES systems to office buildings in Saudi Arabia which results in more peak electrical energy savings and reduced cooling load demands. They also pointed out that on the energy generation side these CTES systems cools down the incoming air entering the turbine and that increases the turbine performance by 30%. Hence, it is obvious that CTES systems are much suitable for both energy generation and energy consuming sides as well [144].

Although majority of CTES systems seen practically are based on ice storage principles, stratified chilled water systems are also equally popular. The concept of stratified chilled water system is logically simple but might involve some practical design implications. Nelson et al. [145] undergo experimental investigation on stratified chilled water based CTES system and found that the aspect ratio (length of storage tank L/diameter of storage tank D) is a decisive factor that determines the thermal performance of such systems. They also concluded that by increasing the mass flow rate and initial temperature gradient of the HTF along with the aspect ratio of stratified tank, the percent rate of cold energy extraction during discharge cycle of the CTES system is increased considerably. Schematic representation of the test system and its mode of operation are presented in Fig. 22.

Temperature distributions in the full-scale stratified chilled water tank provided with double ring octagonal slotted pipe diffusers were characterized by Bahnfleth and Song [146]. They recorded the chilled water temperature profiles in the tank corresponding to the flow rate and inlet temperature which varied from 50% to 95% of the design value. Higher flow rates caused the temperature of chilled water to rise inside the tank and the stratification effectiveness was expected to be reduced during charging. At the same time the thermocline thickness measured in the tank was about 1 m for low and medium flow rates but for higher flow rates the variation in thickness observed was substantial. Implementation of slotted pipe diffusers has minimized the mixing losses at higher flow rates as well as increased the half-cycle figure of merit (FOM) to about 80–88% of full cycle value. But, this trend calls for further improvement in the diffuser design which would in turn restrain the effects of convection losses and limit bulk temperature rise below the thermocline being formed.

In succession to the work executed as above [146], Karim [147] has designed and developed a new stratified chilled water CTES system equipped with octagonal diffusers in order to evaluate its thermal performance for different operating conditions. Thermal stratification in the tank was observed to be complete without any eddy formation but with increased mass flow rate of chilled water and pressure drop at the inlet of diffuser component has reduced the stratification efficiency of the tank. This was due to the improper mixing of warm chilled water with the cold one. Thermal conduction through the tank walls and thermocline increased its thickness and its shape was chiefly decided by the mixing ratio of chilled water in the tank. By providing octagonal shaped diffusers the thermal performance of the stratified tank was better while compared

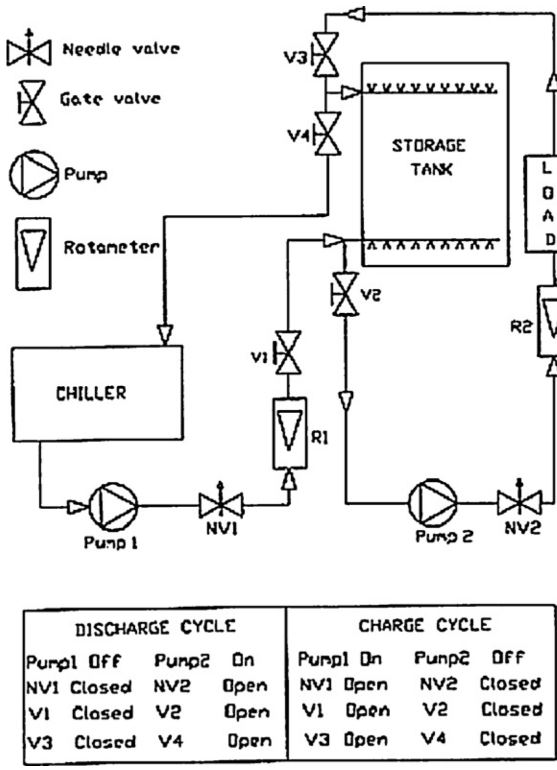


Fig. 22. Schematic representation of experimental test rig [145].

to the distributed diffusers. Thermal efficiency of the developed stratified tank was expected to achieve 90% and this paved way for its implementation in actual CTES applications for ensuring good energy management in buildings.

Reasonable quantity of research works dealing with the stratified chilled water CTES systems have been collectively presented by Haller et al. [148]. Characterization of stratified chilled water thermal storage systems based on charging, storing and discharging processes, thermal performance and stratification efficiency were reported and discussed. From the classical segment of CTES systems chilled water storage (CWS) technique has attracted the technological vision of engineers and researchers from many countries through its operational significance of shifting on-peak electrical power demand to periods of lower demand. In this perspective, Sebzali and Rubini [149] studied the importance of implementing CWS system for advancing the energy performance of air cooled chillers (ACC) serving the cooling load requirements for building located in Kuwait. Operating the ACC in conjunction with the CWS system yields up to 100% reduction in peak electrical energy consumption and would also reduce the chiller size by 33% depending on the type of storage method adopted. The CWS system described in this work actually reduced the power consumed by ACC for charging the storage by 4% in full storage mode whereas in partial storage scheme it increased the power consumption by 4%. This trend suggests that CWS system working with full storage strategy is most suitable for Kuwait buildings and it could also be coupled with partial storage schemes without incurring additional cost.

Henze et al. [150] designed a LHES system combined with chilled water plant that is dedicated for meeting out the cooling load requirements of pharmaceutical buildings. The LHES system supplements the cooling load to be met by single-stage absorption chillers to the electrically driven centrifugal chillers and paved way for improved thermal efficiency and performance of the chilled water plant. As to extend the scope of this work, authors recommend for developing a feasible and optimal strategy for practical implementation of the aforesaid CTES A/C systems in these buildings.

Boonnasa and Namprakai [151] elucidated the application of CWS system for an academic building located in Thailand. They concluded that the CWS system was capable of shifting electrical power demand from peak periods to off-peak hours and reduced the capacity of mechanical chillers by two times. The on-peak power demand was actually reduced by 31.2% and energy consumption by 35.7%. The CWS system performed well in terms of both technical and economic aspects.

Rahman et al. [152] checked the feasibility of incorporating CTES in an institutional building in Australia that is subjected to subtropical climatic conditions. The demand side management of CTES system was analyzed for full and partial storage methods. Using verified simulated model generated with DesignBuilder (DB) software the proportion of acquiring peak load shaving and energy efficiency through these methods was reported. Compared to the conventional cooling system in the building, CTES system operated under full, partial demand limiting and load leveling storage methodologies results in electricity cost savings of 61.19%, 50.26% and 33.94% respectively.

The thermo-economic versatility of this CTES system implies for its potential application in buildings located in subtropical regions. Hasnain [153] and Saito [154] made efforts to disseminate the ideas behind the concepts, design and development of various CTES systems through their review works. The articles referred in these works would represent positive approach towards developing reliable CTES systems for modern building cooling applications. In short, active systems especially CTES systems would generate energy-cost benefits through shifting on-peak cooling load or power demand to off-peak hours. Properly designed systems can reduce chiller size and contribute for attaining improved energy efficiency in buildings.

The distinctive heat storage capacities and enhanced thermal response of various PCMs for passive and active cooling/heating applications in buildings have been identified by several research teams. Some of these research works have been reviewed and are tabulated in Table 7 . Extensive review studies devoted on the basic concepts, heat transfer mechanisms, phase change characteristics, mathematical formulation, simulation analyzes and applications of various PCMs and LHES systems for buildings have been reported [180–185]. Referring to these review works would guide through understanding the thermophysical science involved, and would rejuvenate new ideas for the successful development of these materials and systems for the future energy efficient buildings. Specifications of LHES and CTES tanks that are commercially available from different manufacturers are listed in Tables 8 and 9.

4.3. Nanotechnology based heat energy storage

Nanoscience and nanotechnology has attracted the interests of various research communities involved in engineering and technological fields worldwide. Nanotechnology involves synthesis of particles of size ranging between 1 and 100 nm that show excellent physical and chemical properties. The surface to volume ratio of nanoparticles is higher which facilitate them to be used with PCMs for storing and releasing energies upon demand. PCMs impregnated or encapsulated with nanoparticles exhibits much improved thermophysical properties than in its pure state. Some specific research works performed on LHES systems using nanoparticles have been reviewed and presented in this section.

Khodadadi and Hosseinizadeh [186] developed numerical models and investigated the freezing and melting characteristics of PCM containing dispersed nanoparticles using computational domain. Inclusion of copper nanoparticles of mole concentrations of 0.1 and 0.2 in to the base PCM has reduced the overall freezing time which is

Table 7
Summary of exemplary PCMs (in terms of thermal response) suitable for building cooling and heating applications.

PCM considered	Type of PCM	Objectives of study	Property of PCM			Key observations	Methodology	Application	Reference
			Fusion temperature (°C)	Latent heat of fusion (kJ/kg)					
				Solid phase	Liquid phase				
Sodium thiosulphate-5-hydrate	Salt hydrate	Investigate thermophysical properties, melting and freezing characteristics	48.5	201	–	PCM transition temperature, enthalpy of fusion, specific heat is determined using DSC measurements and relative method. Experimental measurements show 2–3% deviation from literature reports	Experiment	Low temperature solar space heating	Enein and Ramadan [155]
Zinc nitrate-6-hydrate			37.0	141	127				
Barium hydroxide-8 hydrate			78.5	–	260				
Palmitic acid	Fatty acid	Investigate thermal performance and storage parameters	61	203.4	–	Melting and solidification characteristics in radial and axial directions and vertical and horizontal positions. Heat storage efficiency of the PCM tube is evaluated to be 53.3%	Experiment	Heating in buildings	Sari and Kaygusuz [156]
Stearic acid and palmitic acid mixtures	Fatty acid esters	Examine thermal characteristics of series of fatty esters	17–34 (melting) 20–32 (freezing)	110–200	–	Tailored mixtures of fatty esters using methyl esters are prepared and performance tested. These mixtures show good melting and freezing characteristics and demonstrate the merits of combining different PCMs with specific inversion temperatures and latent heats of fusion	Experiment	Space heating and cooling acquiring comfort indoor temperature, central heat storage	Feldman et al. [157]
Eutetic mixtures of lauric acid and palmitic acid (LA–PA)	Fatty acid	Analyze thermal characteristics using vertical concentric pipe-in-pipe energy storage system	35.2	166.3	–	Temperature distribution in radial and axial directions of PCM, heat transfer coefficient between PCM and heat transfer fluid pipe, heat fraction during melting and freezing processes and heat recovery rate are demonstrated. LA–PA PCM mixture reveal improved thermal and thermophysical characteristics	Experiment	Solar heating	Tuncbilek et al. [158]
Stearic acid and expanded graphite composite	Fatty acid	Study of synthesis and characterization of composite PCM	53.12 (melting) 54.28 (freezing)	155.7	155.5	Established charging and discharging characteristics of composite PCM and its three kinds, microstructure and thermal properties using DSC, XRD and FTIR measurements. No outflow of stearic acid from the composites is detected and is thermally stable even after several repeated cycle tests	Experiment	Thermal energy storage in buildings	Fang et al. [159]
Methyl stearate, methyl palmitate, cetyl stearate, cetyl palmitate and its mixtures	Fatty acid esters	Examine solid/liquid phase equilibria of PCMs and thermal properties of gypsum and bricks impregnated with these PCMs	22.2–37.8 (melting) 21.8–37.6 (freezing)	175–237	180–240	Thermophysical properties of these fatty acid esters and eutectic mixtures with phase equilibrium and transition properties are obtained. Specific heat of gypsum wallboard and brick construction impregnated with these PCMs is found to be 2 and 1.7 J/g/°C respectively. Wallboards infused with this PCM mixture minimized the overheating and temperature swing issues in building interiors considerably	Experiment	Solar thermal storage	Nikolic et al. [160]

Table 7 (*Continued*)

PCM considered	Type of PCM	Objectives of study	Property of PCM			Key observations	Methodology	Application	Reference
			Fusion temperature (°C)	Latent heat of fusion (kJ/kg)					
				Solid phase	Liquid phase				
Stearic acid	Fatty acid	Measure transmittance of solar radiation through the selected PCM	64.6	155	–	Effects of transmittance on variable thickness of PCM are reported and found significant change in transmittance at PCM thickness of 2–3 cm. Furthermore, for the same thickness, transmittivity of this PCM at liquid state is higher than glass	Experiment	Space heating, heat insulation in buildings, minimize solar radiation overheating of indoor spaces	Buddhi and Sharma [161]
Hexdecane and tetradecane mixtures	Paraffin wax	Report phase transformation of this binary PCM mixture through numerical model and experimentation	18.1 (hexadecane) 5.8 (tetradecane)	236 (hexadecane) 227 (tetradecane)		Non-isothermal melting of binary mixture PCM is simulated. Temperature distribution in PCM and generation of liquid fraction with respect to plate temperature is experimentally verified. Prediction of solidus and liquidus temperature profiles of this binary mixture PCM for various heating rates is possible using DSC curves	Numerical simulation and experiment	Thermal energy storage in buildings	Kousksou et al. [162]
PCM and water	–	Develop accurate method to obtain heat storage density and compare it with arbitrary temperature ranges	19.5	200	–	Heat storage density for variety of PCMs can be established and compared for varying temperature ranges. Developed calculated data table/two dimensional plot can be used to identify requirements on heat exchangers and heat transfer mechanism in PCMs	Theoretical investigation	Thermal storage in buildings	Mehling et al. [163]
Paraffin compound	Paraffin based	Report the effects of combining PCM with structural insulated panels (SIPs)	25	131	–	PCM integrated into SIPs yields reduced wall heat flues during peak load conditions and minimized indoor temperature fluctuations	Experiment	Building cooling and air conditioning	Medina et al. [164]
Tetradecane–hexadecane mixtures	Paraffin	Study of PCM properties with and without heat generation parameter during phase change process	5–9.6	121.8–227	–	Heat generation found in PCM reduced solidification but speeds up melting process. Tetradecane–hexadecane mixtures demonstrated good heat transfer characteristics	Numerical simulation and experiment	Space cooling	Kalaiselvam et al. [165]
n-Nonadecane/cement composites	Organic based	Establish thermal characteristics and thermal stability	31.86 (melting) 31.82 (freezing)	64.07	69.12	n-Nonadecane as PCM with cement as supporting material reveals good thermal stability and heat resistant capabilities. Seepage of liquid n-nonadecane from the composites is prevented and exhibited appreciable thermal stability	Experiment	Heat storage in buildings	Li et al. [166]

Shape stabilized phase change material (SSPCM)									
Caprylic acid/1-dodecanol eutectic binary mixture	Fatty acid based	Determine thermal properties of eutectic PCM mixture	6.52	171.06	–	Thermal properties are determined using DSC measurements and accelerated thermal cycle tests. Demixing and segregation effects observed at 30% concentration of PCM has improved the thermal storage characteristics and thermal stability even after 120 thermal cycles	Experiment	Cool thermal storage and air conditioning	Zuo et al. [167]
Epoxy resin (EP) based polyethylene glycol (PEG)	Organic based	Investigate mechanical and thermal stability of shape stabilized EP/PEG PCM	54.2	132.4	–	Characterization of EP/PEG PCM is performed and thermophysical properties are determined. Mechanical deformation of this PCM due to heat is reported to be very small. No change in its shape during phase transformation process is observed. PCM exhibited good mechanical and thermal stability	Experiment	Heating in buildings	Fang et al. [168]
PEG/diatomite composite	Organic based	Typify chemical compatibility, thermal storage potential and stability of composite PCM	27.7 (melting) 32.19 (freezing)	82.22	87.09	Chemical and thermal characterization of the composite PCM notified improved performance and stability. Extended graphite added in different proportions into the PCM has enhanced thermal conductivity and heat transfer rate significantly. Wallboard made of this PCM composite reduced temperature fluctuations and maintained the indoor temperature at 26.45 °C	Experiment	Cooling in buildings	Karaman et al. [169]
Polytehylene glycol (PEG)-active carbon (AC)	Organic based	Study of thermal and structural properties of PEG/AC shape stabilized PCM	–	72.8–85.1	81.3–90.2	Prepared SSPCM is characterized and performance tested by varying the weight percentage and molecular weight of PEG. Supercooling effects in the PEG/AC PCM is found very less than pure PEG PCM due to inclusion of mesoporous AC component in SSPCM. Thermal and structural stability is significantly improved	Experiment	Thermal energy storage in buildings	Feng et al. [170]
Paraffin/high density polyethylene (HDPE) composite	Paraffin based	Demonstrate effects of graphite additives on thermophysical parameters of SSPCM	44–46	88–110	–	Thermal properties of SSPCM are found improved by using extended graphite (EG) and graphite (GP) additives. Melting temperatures are found to be constant. Latent heat is observed to well agree with theoretical values. Heat conduction is enhanced	Experiment	Heat storage in buildings	Cheng et al. [171]
Paraffin compound SSPCM	Paraffin based	Investigate thermal characteristics of several samples of paraffin-based SSPCM	20–25 (building) 40 (underfloor)	120–160	–	Fusion temperature of SSPCM can be altered by adding different concentrations of paraffins. Optimal composition of paraffin in this SSPCM is found to be 80%. SSPCM developed is able to manage temperature swings in indoor environment	Simulation and experiment	Solar space heating in buildings, underfloor electric heating	Zhang et al. [172]
SSPCM	–	Numerically investigate the thermal performance of SSPCM plates for cooling indoor environment in summer	26	160	–	Simulation analysis on SSPCM plates used as inner lining in building that is combined with night ventilation scheme results in reduction of per day maximum indoor temperature to 2 °C. Air change rate requirements are also dealt with. Thermophysical properties of SSPCM plates are determined	Numerical simulation	Space cooling in buildings combined with night ventilation	Zhou et al. [173]

Table 7 (*Continued*)

PCM considered	Type of PCM	Objectives of study	Property of PCM			Key observations	Methodology	Application	Reference
			Fusion temperature (°C)	Latent heat of fusion (kJ/kg)					
				Solid phase	Liquid phase				
Microencapsulated phase change material (MPCM)									
Polymethyl-methacrylate (PMMA)/docosane	Organic based	Analyze morphologies, chemical, mechanical and thermal stabilities	41 (melting) 40.6 (freezing)	−48.7	54.6	Morphological results indicate smooth and compact surface of PMMA/docosane PCM. Test results infer PCM is stable at high temperature and stable as well	Experiment	Solar space heating	Alkan et al. [174]
Encapsulated MPCM	Paraffin wax	Prepare MPCM by complex coacervation and spray drying methods and examine characteristic properties	–	145–240	–	Spherical shaped uniformly sized MPCM developed has exhibited high rate of heat storage and release capacities. Core-to-coating ratio, emulsifying time and quantity of cross-linking agent influence MPCM efficiency significantly	Experiment	Solar energy storage	Hawlader et al. [175]
PMMA/n-eicosane	Organic based	Investigate morphologies, mechanical and thermal stabilities	35.2 (melting) 34.9 (freezing)	−87.5	84.2	MPCM show better heat transfer characteristics, mechanical, thermal and chemical stabilities even after 5000 cycles	Experiment	Heat storage by integration with building elements	Alkan et al. [176]
Micronal BASF	Paraffin based	Establish the use of microencapsulated PCM in sandwich panels to increase thermal inertia	26	100	–	Selected MPCM having 5 μm size particles embedded in sandwich panels exhibited improved thermal inertia without adding additional mass to sandwich panels	Experiment	Heat storage in buildings through sandwich panels	Castellón et al. [177]
DPNT06-0182 Micronal DS 5008X	Paraffin based	Analyze thermal, chemical and flow properties of MPCM samples	35.6 28.7	102	97	Spherically shaped and smooth surfaced MPCM and its samples (MPCM slurries) show agreeable performance in terms of thermal stability, charging and discharging properties. Higher the temperature, lower the dynamic viscosity observed. MPCs tested are in the Newtonian fluid range of shear rate 200/s and mass fraction < 0.35	Experiment	Solar space heating	Zhang and Zhao [178]
Hexadecane Amino plastics	Organic based	Study of phase change characteristics and supercooling effects on MPCM slurry	18	234	–	Results indicate that deployment ratio of MPCM slurry in actual A/C system equipped with TES depends on the final temperature close to 8 °C. 80% of latent heat transfer occurred by using MPCM slurry	Experiment	Thermal energy storage in buildings	Zhang and Niu [179]

Table 8
Specifications of LHES tanks manufactured commercially [64,69,232].

Volume (m^3)	External diameter (mm)	Total length (mm)	Outer surface area for insulation (m^2)	Inlet/outlet connections (mm)	Cradles required	Weight measured at empty (kg)	Volume of HTF (m^3)
Cristopia energy systems (cristopia)							
2	950	2980	10	40	2	850	0.77
5	1250	4280	18	50	2	1250	1.94
10	1600	5240	29	80	2	1990	3.88
15	1900	5610	37	100	2	2900	5.82
20	1900	7400	47	125	3	3700	7.77
30	2200	8285	61	150	3	4700	11.64
50	2500	10,640	89	175	4	6900	19.40
70	3000	10,425	106	200	4	7300	27.16
100	3000	14,770	147	250	6	12,700	38.80
Environmental process systems limited (EPS Ltd.)							
5	1250	3750	–	50	–	–	–
10	1600	4500	–	80	–	–	–
25	2000	8000	–	125	–	–	–
50	2500	10,000	–	150	–	–	–
75	3000	10,600	–	200	–	–	–
100	3000	11,100	–	250	–	–	–

Table 9
Specifications of ice-CTES tanks manufactured commercially by CALMAC Manufacturing Corporation [270].

Volume (m^3)	External diameter (mm)	Total length	Floor loading (kg/m^2)	Inlet/outlet connections (mm)	Net usable capacity (kWh)	Weight measured at empty (kg)	Volume of HTF (l)	Volume of ice/water (l)
Model A storage tank								
4.23	1875	–	718	51	144	265	151	1550
7.31	1875	–	1382	51	288	465	295	3105
8.84	2260	–	1142	51	345	555	341	3710
9.04	1875	–	1758	51	369	580	375	3955
13.13	2260	–	1894	51	570	885	560	6265
Model C storage tank								
7.78	–	1940	1396	101	288	485	326	3105
9.33	–	2340	1157	101	345	580	341	3710
9.42	–	1940	1772	101	369	595	375	3955
13.70	–	2340	1909	101	570	910	594	6265
27.04	–	4620	1909	101	1140	1815	1192	12,530
40.45	–	6910	1909	101	1710	2720	1787	18,795

attributed to the improved thermal conductivity of nanofluid and consumes less energy per unit mass to freeze the PCM. The high energy discharge rate of nanoencapsulated PCM observed made it as a potential candidate for LHES applications.

Fang et al. [187,188] synthesized nanoencapsulated PCM with polystyrene as shell and n-octadecane as the core using ultrasonic-based in situ polymerization technique. Fig. 23 shows the transmission electron microscopy (TEM) image of the nanoencapsulated PCM. Characterization and morphological identifications reveal that nanoparticles of size ranging 100–123 nm are produced with latent heat of fusion of the nanoencapsulated PCM determined to be 124.4 kJ/kg. This value almost coincides with the calculated values for pure PCM. Polymerization factors augmented the heat capacity of this PCM to 11.61 kJ/kg K and improved the thermal stability and viscous effects as well. These parameters enabled the PCM based nanofluid suitable for heat energy storage purposes. A novel study that describes the enhancement of thermal properties, transport phenomena and heat interactions of palmitic acid based PCM entangled with multi-walled pristine carbon nanotube (PCNT) fillers for heat storage purposes are presented by Wang et al. [189]. PCNT composites prepared by mechano-chemical reaction process upon dispersed in the base PCM has increased the thermal conductivity to 30% than the previously reported values. The degree of improvement in thermal conductivity made the nano-based PCM to be an ideal candidate for enhancing the performance of thermal energy storage systems.

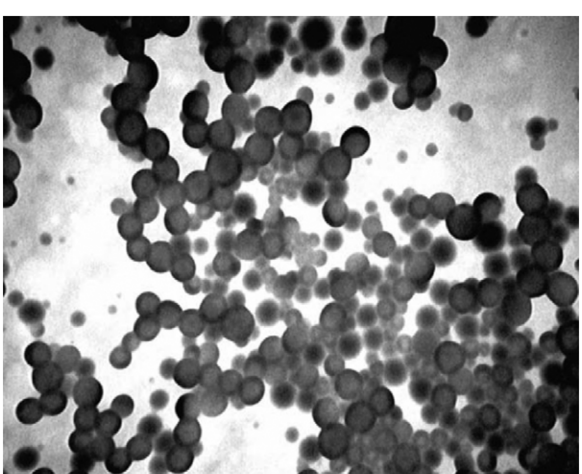


Fig. 23. TEM image of nanoencapsulated PCM [187].

Liu et al. [190] conducted an experimental work of suspending small quantities of titanium dioxide (TiO_2) nanoparticles into the saturated aqueous solution of barium chloride ($BaCl_2$). Thermal conductivity of this nanofluid PCM is increased by 15.65% while the concentration of nanoparticles is increased by 1.13%. As a result the time taken for storing and releasing energies was reduced and attributed to the enhanced thermal conductivity, nucleating and heat transfer interactions of nanoparticles dispersed in the PCM. Nanofluid PCMs with higher thermal conductivity are much preferred in CTES systems to experience enhanced heat transfer mechanism between HTF and the PCM with less heat losses from the system.

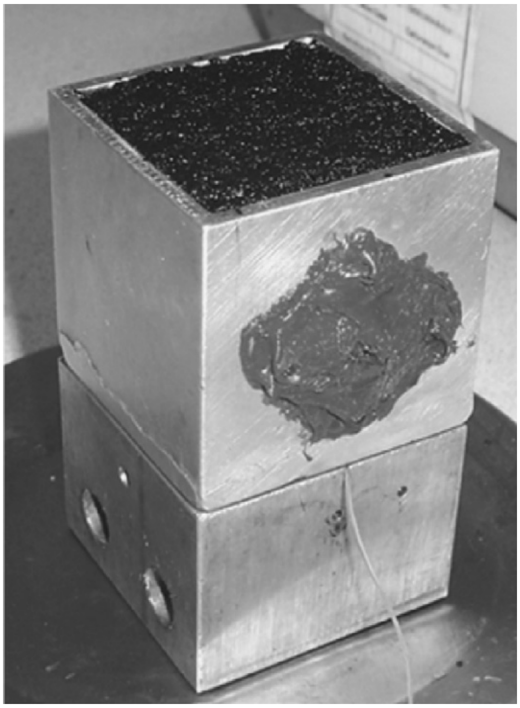


Fig. 24. Pictorial representation of 5.08 cm cubic thermal containment unit with the heated base unit [196].

Fang et al. [191] dealt with n-tetradecane oil and urea-formaldehyde resin based nanoencapsulated PCM (NEPCM). NEPCM subjected to structural and thermal characterization shows nanoparticles of 100 nm size well encapsulated the PCM which made the NEPCM to exhibit good melting and freezing characteristics. Addition of resorcin (cross-link agent) upto 5% increased the n-tetradecane (PCM) concentration by 61.8% and stimulated heat transfer interactions of NEPCM further. Heat of fusion of this NEPCM ranged from 100 to 130 kJ/kg and has fusion temperature in the range suitable for thermal storage applications. NEPCM has an enormous potential to be integrated with conventional heat storage systems and would improve the overall thermal performance of the LHES systems. Similar studies dealing with different nanoencapsulation techniques with nanoparticles dispersed in varied concentrations and other combinations for the development of PCMs with high energy storage densities, better thermophysical characteristics, enhanced heat transfer properties and flame resistant characteristics have been performed in recent years [192–195].

Compared to the regular studies done on the melting characteristics of PCM, Sanusi et al. [196] made a different approach to investigate the thermal performance of PCM during solidification process with the use of graphite nanofibers as thermal conductivity enhancers. Photographic view of 5.08 cm cubic thermal containment test unit with heated base arrangement is depicted in Fig. 24. They have concluded that with aspect ratios of the cubic thermal containment units (TCU) of 0.5 and 2 with total volumetric capacity of 1260 cm^3 the solidification time of PCM was decreased considerably. For smaller mass of PCM at an aspect ratio of 1, due to the enhanced thermal conductivity of graphite nanofibers a reduction in the total solidification time for the PCM was reported. This is not the case for larger mass of PCM contained in the TCU. Figure of merit analysis suggests that infusion of graphite nanofibers in the PCM enhanced the thermal diffusion effects.

On the other hand, the time required for initiating melting process within the PCM was largely delayed due to the presence of graphite nanofibers. This is a vital parameter to be considered and addressed during solidification cycle for PCMs embedded with graphite nanofibers. Constantinescu et al. [197] demonstrated a new way to amalgamate nanocomposite materials with building elements which can collectively contribute for reducing thermal load demand and carbon foot prints as well. They used polyethylene glycol, aluminum, epoxidic resin and three-ethylene-tetramine (TETA) hardener compounds at different proportions and mechanically processed them to obtain the required nanocomposites PCM. Scanning electron microscopy (SEM) images of P10-E, P20-E and P25-E composites is represented in Fig. 25. Qualitiative and quantitative measurements conducted reveals that the nanocomposites with latent heat of fusion above 100 J/g is more suitable for incorporating it in sandwich panels or wallboard fixtures for passive heating/cooling applications. Furthermore, the nanocomposites designated as P10-E and P15-E showing lower fusion temperatures are recommended for use in active LHES systems. Besides, P20-E type of nanocomposites prepared in this study can be used for insulation and structural support of heat pipe assemblies.

A recent study of Wu et al. [198] considers suspending small quantity of copper nanoparticles in paraffin PCM to determine its heat transfer characteristics and thermal properties during phase change processes. This work differs from the one performed in [186] that melting paraffin was selected as the PCM in this work rather than water. Characterization and thermal cycling tests performed on the copper nanoparticles-based paraffin PCM shows 11.1% and 11.7% reduction in latent heat transfer during melting and solidification cycles. Similarly, the heating and cooling rates were reduced by 30.3% and 28.2% for 1% by weight of copper nanoparticles suspended into the paraffin PCM respectively. The change fusion temperature was infinitesimal thereby; the net heat transfer rate during charging and discharging processes were augmented accordingly. Thermal degradation, heat loss effects, chemical and mechanical stability were also improved considerably. All these factors help this PCM to be suggested for TES operations.

Yavari et al. [199] analyzed the thermal conductivity improvement in 1-octadecanol (an organic PCM) by including low concentration graphene nanoparticles. It was estimated that, by adding 2% equivalent by weight of graphene platelets to the organic PCM has increased the thermal conductivity by 63% with only 8.7% reduction in phase change enthalpy or heat storage capacity while compared to multi-walled carbon nanotubes. On an average, by adding 4% equivalent by weight of graphene to the PCM elevated its thermal conductivity by 140% with only 15% decrease in the latent heat storage capacity. Compared to silver nanowires and multi-walled CNT [189] fillers, inclusion of nanostructured graphene platelets increased the thermal conductivity of the organic PCM. It is imperative to use this kind of PCM in LHES systems to achieve impetus growth in heat energy storage technology.

The extent of research studies carried out for developing nano-based PCMs for thermal energy storage applications shows a positive lift in the current technological advancements and that would contribute for gaining overall building energy efficiency in forthcoming years.

4.4. Energy storage potential

LHES systems integrated with building heating/cooling elements or utilities offers substantial energy storage capabilities and would help to reduce the overall building energy consumption especially during on-peak load conditions. Table 10 provides ease information on the energy storage capacity, discharge ability, efficiency and storage time for various TES systems. The major outcomes from a variety of research contributions have been reviewed and summarized in Table 11 . Most of these studies have pointed out the energy storage capabilities of PCMs that would influence on thermal and energy efficiency of passively and actively

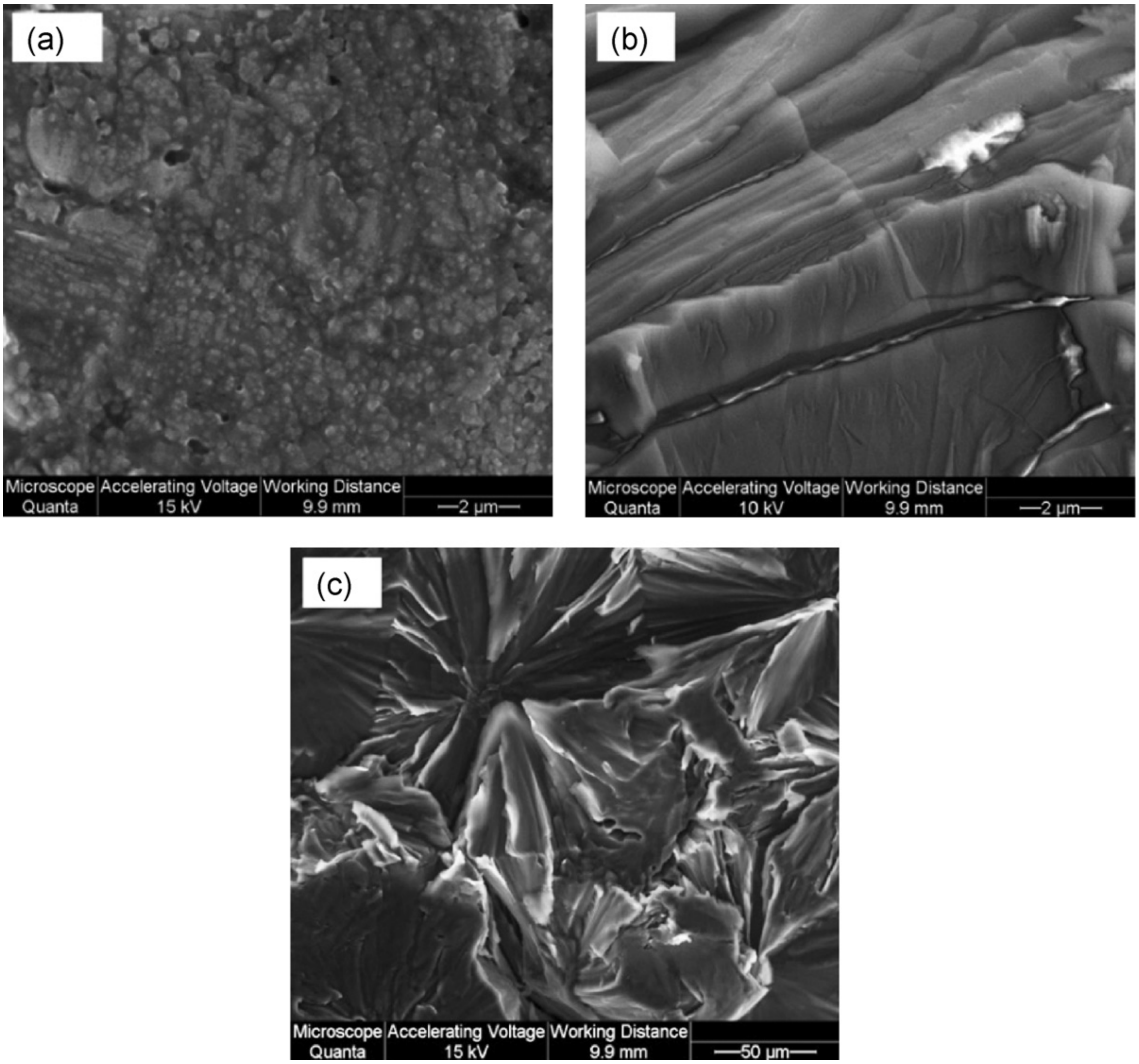


Fig. 25. SEM images: (a) P10-E; (b) P20-E; (c) P25-E composites [197].

designed buildings. Maintaining the indoor temperature fluctuations to lower levels is of prime concern reported in these studies.

Archetype experimental methodologies and numerical simulations followed by experimental validations for predicting the dynamic behavior of PCMs on the building thermal performance are also been dealt with. Concept of the free cooling/night ventilation was also given importance in these studies and the positive effects of implementing this principle to LHES systems are largely explained.

5. TES systems for high performance buildings

As mentioned in the earlier sections, power and energy consumption would be the maximum for buildings that are not equipped with energy efficient systems. Any building, whether new or subjected to refurbishment, can be made to perform well by adopting value-added design principles and procedures while constructing. In this account, buildings incorporated with energy efficient conventional and/or renewable energy source based systems for its daily operations would definitely drive-in high performance. These buildings would ensure to possess good healthier indoor environment and comfort conditions for its occupants, operate with the minimum possible life cycle costs, reduced environmental impacts without sacrificing energy efficiency. Pertaining to the scope of this paper, the possibility of implementing solar energy based TES systems has been reviewed and the observations made from various research studies are presented in this section.

Table 10
Key parameters of various active TES systems [202].

TES system	Energy storage capacity (kWh/t)	Discharge ability (kW)	Efficiency (%)	Storage period
Chilled water storage	20–80	1–10,000	50–90	Day-year
Aquifer storage	5–10	500–10,000	50–90	Day-year
Borehole storage	5–30	100–5000	50–90	Day-year
Ice storage	100	100–1000	80–90	Hour-week
PCM storage	50–150	1–1000	75–90	Hour-week

Table 11
Summary of major results from various research studies.

PCM considered	PCMs integration	Objectives of study	Key inferences	Methodology	References
Paraffin type PCM					
Paraffin-based PCM	The phase change wallboard containing 20% by paraffin mass	A prototype IEA building located in California climate condition was selected	28% of the peak cooling load was expected to be reduced	Simulation	Stetiu and Feustel [200]
Paraffin-based RT 54 Rubitherm GmbH	PCM storage tank coupled with building envelope made of concrete	Building to be incorporated with solar system that is situated in Blacksburg, VA was chosen for the analysis	Yearly heating energy-cost was reduced by 61.5%	Simulation	Hassan and Beliveau [201]
RT25 (12 mm) and S27 (8.6 mm)	PCMs located in transparent plastic containers placed behind a double glazing with an air gap of 10 mm	Investigated on a south facade panel in Würzburg, Germany	25% of energy gains can be reduced in summer; likewise 30% heat losses and 50% solar heat gains can be reduced in winter	Experiment and simulation	Weinlader et al. [37]
Highly crystalline, n-paraffin-based PCM	PCM infused into the frame walls	A full instrumented test house of 1.83 m × 1.83 m × 1.22 m in Lawrence, Kansas, USA was investigated	The space cooling load and the average wall peak heat flux were found to be reduced about 8.6% and 15% respectively	Experiment	Zhang et al. [104]
Paraffin-based PCM	PCM is in thin-walled copper pipes and inserted into horizontal slotscut into the polystyrene foam	Fully instrumented test house of 1.83 m × 1.83 m × 1.22 m was analyzed	The peak heat flux can be reduced by 37% and 62% using a PCMSIP with 10% and 20% PCM concentrations	Experiment	Medina et al. [164]
n-Paraffins mixture	PCM impregnated into the ceiling board	Test the performance of the PCM ceiling board in an office building at Tokyo, Japan	Running cost of this LHES system was reduced by 96.6% than the conventional rock-wool ceiling board.	Simulation	Kondo and Ibamoto [203]
PCM composed of foamed glass beads and paraffin waxes	PCM was embedded directly below OA floor boards in the form of granules	A small experimental system with a floor area of 0.5 m^2 was investigated	89% daily cooling load can be stored in night using a 30 mm thick packed bed of the granular PCM	Experiment	Nagano et al. [46]
Mixture of commercial glycol wax	Incorporated in walls and roofs	An existing building in Campinas, SP, Brazil was considered	Save 19% and 31% energy for cases using window and central AC units	Simulation and experiment	Ismail and Castro [204]
Paraffin-based PCM	Building interior and exterior wall structures were finished with PCM wallboards	Thermal performance of PCM wallboards were examined in a residential building (17 × 13 × 3 m) located in Boston	Possible cost savings up to $190 was recognized with these PCM wallboards. Economic analysis suggests for a 3–5 years payback period for these PCM wallboards	Simulation using TRNSYS software	Stovall and Tomlinson [205]
K18 with an average melting temperature of 25.6 °C	Integrated in walls and roofs	Study includes concrete sandwich walls, low-mass steel walls under the typical meteorological weather data in Dayton, Ohio	The peak loads can be reduced by 19%, 30%, and 16% in concrete sandwich walls, steel roofs and gypsum wallboards respectively	Simulation	Kissock and Limas [206]
Graphite added paraffin-based PCM	Incorporated in ceiling	Improve energy storage potential with increase in thermal conductivity	Energy storage capability was enhanced by 12% by using graphite–paraffin-based PCM plates applicable for night ventilation	Experiment	Marin et al. [207]
Paraffin-based PCM	PCM embedded in the ceiling panel	Capture more solar radiation entering through windows onto the PCM for the office building	Heat loss from room can be recovered by 17–36% over the initial gains	Experiment	Gutherz and Schiler [208]
Paraffin-based PCM	Two layers of PCM floor structure integrated with other floor construction materials	Investigate the heat storage and release capacities of double layer PCM floor to offset peak load shaving and acquire energy savings	Energy release rate of PCM embedded floor structure increased heating and cooling load by 41.1% and 37.9% respectively	Simulation	Jin and Zhang [209]

Table 11 (*Continued*)

PCM considered	PCMs integration	Objectives of study	Key inferences	Methodology	References
Salt hydrate type PCM					
Calcium chloride hexahydrate ($CaCl_2 \cdot 6H_2O$) salt hydrate	Cylindrical polyvinyl chloride (PVC) enclosure containing PCM was placed in the storage tank	Study the heat transfer characteristics and energy efficiency of solar-assisted heat pump using this PCM storage technique at the Karadeniz Technical University	Conserved 9390–12,056 kWh of total energy spent on heating in winter season than by using various other heating utilities	Simulation using SOLSIM software and experiment	Kaygusuz [210]
Salt type PCM that is held in stasis by a perlite matrix	Between two layers of insulation in a configuration known as resistive, capacitive, resistive	A geometry in which the wall/ceiling structure was assumed as a three-layer plane wall having the PCM in the center layer	The results suggest that 19–57% of maximum reduction in peak load as compared to a purely resistive R-19 wall can be achieved	Simulation	Halford and Boehm [211]
Calcium chloride	PCM filled in pipe was placed under the floor	Develop solar space heating system for residential buildings in UK	Experimental results suggest that heating energy consumption by heating utilities can be reduced by 18–32%	Experiment	Kenneth [212]
Fatty acid type PCM					
Butyl stearate (25% by weight)	PCM impregnated with gypsum wallboard and acts as lining in interior of the test building room	Test the energy storage capacity of PCM–gypsum wallboard in an outdoor test building room of 2.82 × 2.22 × 2.24 m size located in Montreal	Total heating energy savings up to 15% was accomplished using the PCM wallboard	Simulation and experiment	Athienitis et al. [213]
Fatty acids	PCM combined with gypsum used as wallboard lining in interior of the room	Fully glazed multi-zone naturally ventilated building was considered for investigation	Substantial reduction of heating energy demand in winter was achieved by a value of 90%	Simulation using ESP-r	Heim and Clarke [214]
Hexadecane $C_{16}H_{34}$	Microencapsulated PCM slurry stored in slurry tank	Demonstrate the energy savings potential of hybrid system that combines chilled ceiling, MPCM slurry storage and evaporative cooling methodologies for five representative climatic cities in China	Energy savings potential of 80% and 10% were acquired in the northwestern China and southeastern China respectively	Simulation	Wang et al. [215]
Capric acid/n-octadecane	Building wall contains PCM spherical capsules of size 64 mm in diameter	Simultaneous management of solar and electrical energy in building was evaluated for a room of 5 × 5 × 3 m that has PCM storage wall thickness of 192 mm	Peak electricity utilization was conserved by 30–32% for space heating in building	Simulation	Hammou and Lacroix [220,223]

5.1. Solar-assisted TES systems for passive buildings

Solar energy as known well for its intermittent energy supply due to local and other climatic conditions is still reasoned strongly for its usage in various heating and cooling applications ranging from domestic to industrial systems. The feasibility of utilizing solar energy source chiefly depends on the design of energy storage systems. In this relation, Manz et al. [216] proposed a solar wall system that includes TIM and PCM to heat the indoor space and bring in the daylighting effects as well. Calcium chloride hexahydrate with 5% additives was chosen as the PCM which has heat of fusion of 192 kJ/kg. Parametric investigation reveals that the mean melting temperature was regulated from 26.5 to 21 °C which is an indication of good heat release and captures rates by the PCM. Heat loss observed through the façade of the building was only 1% during the entire operating cycle. It is suggested that to focus on the reliability, thermal and chemical stability of the PCM in large quantities for practical applications and these parameters have been accommodated by other research groups, in recent years. The study conducted in [108] is a good example of this and demonstrate the solar energy storage principles using LHES system for developing high performance buildings.

The process of combining phase change component material (PCCM) with water wall for enabling thermal load leveling in a solarium building was elucidated by Tiwari et al. [217]. The solarium building was numerically analyzed for thermal load leveling in indoor spaces with and without the PCCM–water wall combination as shown in Fig. 26. The high heat transfer coefficient of water wall and the latent heat of fusion of PCCM reduced the temperature fluctuations in the living space and limited it to around 20 °C. Altering the water wall and PCCM thicknesses from 0.1 to 0.05 m the indoor temperature rise by 10 °C and the heat flux entering the living space gets increased by 35%. This kind of flexibility has rendered the PCCM–water wall system to store and release heat energy upon demand in indoor spaces and paved way for its practical usage in passively designed buildings.

Further to the study performed in [90], Darkwa et al. [218] executed thermal simulation on the phase change drywall structures and determined its effectiveness for to integrate it in a solar passive building. They concluded that the laminated PCM wallboard was energy efficient and reduced the indoor minimum temperature during night time 17% more than the randomly distributed wallboard. This signifies the effectiveness of PCM drywalls in terms of better latent heat storage capacity than the random-mixed wallboards and in-line with [90].

Weinlaeder et al. [219] showed interest in developing sun protection system for office buildings wherein they used PCM filled vertical slats for reducing the effects induced by solar gains in indoor spaces. The PCM slats absorbed heat energy from solar radiation and because of its high latent heat storage property it was able to restrain the effects of solar gain thereby; the room temperature was maintained at 28 °C even at peak solar days. The PCM slats decreased the solar gain factor or carrier ‘g’ factor by 0.25 and 0.3 in fully closed and 45° angled positions which was less while compared to the conventional system. Regeneration of PCM during night time has to be ensured by having night ventilation systems provisions to avoid certain issues related to stand-alone mode. Zhou et al. [221] has evaluated the phase change characteristics and thermal performance of SSPCM plates for a south-faced direct solar gain room using enthalpy model analysis. SSPCM plates made as lining material inside the solar room has decreased the indoor temperature swings and provided comfort for the occupants. Heat energy dissipated through wall structures to inside of the room has been effectively absorbed and stored by the SSPCM plates during day hours and released it in night time. By this the degree of thermal comfort attained during night time was enhanced.

Another work presented by authors [224] deals with the SSPCM plates for a solar room located in Beijing, China which has resulted in 47% of normal and peak hour energy savings in summer and 12% of total energy savings in winter. Similar to this, PCM–gypsum plates and SSPCM plates incorporated to a solar room has collectively catered thermal load demand during peak periods. About 46% and 56% of temperature fluctuations in indoor environment were reduced by PCM–gypsum and SSPCM plates respectively, which make SSPCM plates superior than the PCM–gypsum plates for solar-LTES applications in buildings [225]. Indoor thermal comfort criteria were effectively met in these systems.

In conjunction to several research works focusing on attaining indoor thermal comfort conditions using PCM for regular buildings, Jiang et al. [222] tried using numerical approach to design and select optimal PCM fusion temperature and its latent heat for a passive solar room. Optimal phase change temperature depends on the lower limit of indoor thermal comfort, ACPH, overall coefficients of exterior wall and glazing, internal heat source, temperatures of ambient air and room walls. In total, the optimal fusion temperature of PCM varied between 1.1 and 3.3 °C above the lower limit range of thermal comfort. Thus, the PCM can be represented for addressing thermal comfort related issues in tropical climatic regions.

Hassan and Beliveau [201] described the viability of solar collector based LHES system that achieved 61.5% of reduction in yearly electricity consumption for heating purposes in the residential building considered. Approximately, this system delivered 88% of total building space heating demand as well as hot water requirements on a year-round basis. Full-scale experimental evaluation on this system could demonstrate much more benefits of its usage in modern buildings.

Among the various research studies dealt on PCMs, Veerappan et al. [226], Wu et al. [227] and Huang et al. [228] elaborated the phase change characteristics of PCMs that are most viable for solar heating applications. They have identified that the heat flux generation, heat capture and release rates, temperature of the HTF and transition temperature of PCM, nucleating effects of microparticles greatly influence the charging and discharging characteristics of PCM. Time taken for solidification and melting could be lowered by proper choosing and mixing of PCM components, which would exhibit accurate transition temperature and also be thermally stable even after subjected to several heating/cooling cycles. Inclusion of fins or other extended surfaces on to the PCM encapsulation can enhance the overall heat transfer rate and effectiveness of the LHES systems.

Merging variety of PCMs into the building fabrics to offset the heating/cooling load demand has been of great interest in recent times [229–234]. Detailed simulation, experimentation and decision-making by predictive methods for these LHES systems influenced by solar energy source gives out the significance of developing integral design, which would facilitate to understand the thermophysical behavior and heat transfer performance of PCMs for passive solar buildings.

5.2. Solar-aided LHES systems coupled with heat pump

Factually, the basic demarcation seen for an active LHES system as applied for solar energy storage would be intended to provide space heating in buildings rather than space cooling. Most of the research contributions in this category focus on to cater space heating in buildings through LHES system coupled with heat pump arrangement thereby; balancing the gap between the peak heat flux demand in buildings and the renewable energy supply. Different methodologies were adopted for acquiring heating in indoor environments with the aforementioned strategy. To note with, the performance index of these systems chiefly depends on the solar

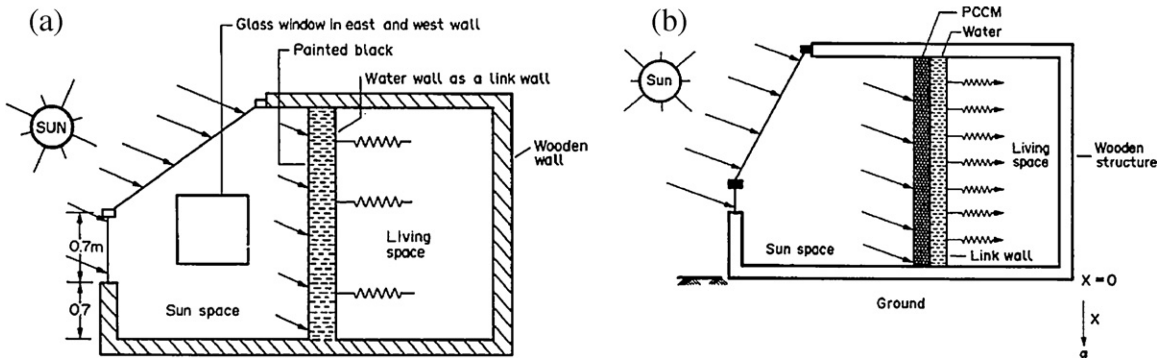


Fig. 26. Schematic representation of solarium having (a) water wall as a link wall, (b) combination of PCCM and water wall as a link wall [217].

energy collection area, heat storage tank design, uniqueness in the thermophysical properties of PCM and the operation of heat pumps during sporadic heat energy supply [235–239]. Table 12 provides an outline of the selected indices for the degree of stratification and stratification efficiency as applicable to solar TES processes.

Any radical changes that would occur in PCM in hot sunny days, partly cloudy or at sun brilliance times has a direct effect on the heat exchange mechanism between the HTF and the PCM. Integration of heat pumps with solar-assisted LHES systems helps to balance or equalize the thermal load sharing requirements during both sun shine and off-sun shine hours and would maintain the indoor environment comfortable for the occupants. LHES systems coupled with the ground (energy) source could still improve the performance of the heat pump units from 4.29 through 21.35. The high performance value of LHES system was because of not operating the heat pumps in extreme cold conditions [240–242].

Characterization of thermal properties of various PCMs may generally be suitable for normal heating and cooling applications in buildings. However, for active solar energy storage systems insinuation of generalized PCMs may involve thermal disturbances or stress, fusion lag, nucleation effects etc. during phase change process. Collection of intense research studies aimed at elucidating the effective utilization of solar-based TES systems for accomplishing cooling and heating in buildings are put forward by Chan et al. [249] and Chidambaram et al. [250].

5.3. Low energy building design

In the quest towards developing high performance buildings the increased potential for TES systems in buildings especially to achieve thermal comfort, reduce heating/cooling load demand and improve energy efficiency has gained momentum in recent years. TES systems are already been into the pace of design concept related to buildings that would consume less energy and has a better performance than the standard energy efficiency needs as recommended by building Codes and Standards.

As part of low energy building design, Hoes et al. [251] used the concept of combining latent functionally PCM and building thermal mass to reduce the effects of peak heat flux and temperature fluctuations in low weight buildings. Adaptation of thermal mass constituents and PCM must be optimal in order to acquire the same benefits of high weight buildings for low weight buildings. The proposed concept has reduced the computed weighted over and under heating periods with a maximum of 1295% while compared to the concept of having conventional permanent low thermal mass in buildings. As of now, the adaptable hybrid TES strategy holds good for moderate climate regions and requires further evaluation for its potential applicability to buildings located in tropical and subtropical climatic regions. The idea of including high insulating materials and PCM microparticles into the thermal mass has also been recognized under low energy building design [252,253]. These studies have also pointed out the effectiveness of using LHES system for providing good thermal environment for the occupants.

In buildings, where it may not be applicable for installation of direct solar energy systems or solar-aided systems used for cooling, systems that would store and release heat energy from underground is most preferable. These systems stores the cold energy dissipated by the surface beneath the earth in summer and would transfer it to the building to satisfy the cooling load. This concept has been known from the ages but to the author's knowledge there are only limited research studies been executed that well describes the functionality of these systems amalgamated with building cooling utilities. Numerical simulations performed have resulted in an increased coefficient of performance (COP) of the overall system. However, to realize higher performance from these systems, in situ testing methodologies have to be developed which would demonstrate its practical usefulness for energy efficient buildings [254,255]. Hierarchical optimization of low energy building operations using advanced intelligent fuzzy controller have been detailed by Yu and Dexter [256]. The fuzzy rule based supervisory control strategy has addressed the discrepancies existing between energy-costs and thermal discomfort costs satisfactorily while compared to the expert controller. In this regard, the computational times of both fuzzy supervisory control and expert control were almost equivalent, but lesser than the optimization based control methods in this regard. Solution to reduce the computational time required for fuzzy control scheme to optimize the performance of low energy building and to produce it on-line is underway in research.

Xing et al. [257] has narrated the importance of advanced technologies for refurbishing buildings that would count for zero carbon potential. The hierarchy laid down would be beneficial to the design engineers and architects to fully understand the energy savings opportunities readily available, which could be implemented at each level of design intent to the construction stage of buildings. TES systems are also a matching part of this trail that supports in both technical and economical aspects for developing low energy buildings.

5.4. Focus on LEED and sustainability

There has been consistent information being passably added about the impact of buildings on both the ecology and the natural environment in dealing with high performance building green building or sustainable design. Green and sustainable design basically differs by the extent to which the design proposed would prove satisfactory performance towards maintaining the ecological balance. Green or sustainable concepts have been framed to almost all workable systems in the field of engineering and technology. Looking onto the building sector, starting from the scheme inception to the complete construction use of environmentally benign

Table 12
Summary of basic characteristics for the selected indices for stratification and stratification efficiency for TES processes [148].

Description/Reference	Degree of stratification index	Efficiency of stratification	Applicable for			Identification of instant of destratification or possible mixing	Isolate mixing from heat losses	Applicable to variable temperatures and mass flow rates	In qualitative agreement with entropy production	Requirement for internal temperature measurement
			Charging	Discharging	Storing/standby					
Thickness of thermocline and related methods	Yes	N/A	Yes	Yes	Yes	Yes	N/A	N/A	–	Yes/N/A
Wu and Bannerot [243]	Yes	N/A	Yes	Yes	Yes	Yes	N/A	-	-	Yes
Charge/discharge efficiencies	N/A	Yes	Yes	Yes	N/A	N/A	N/A	N/A	N/A	Yes/N/A
MIX_{Dav}, Davidson et al. [244]	N/A	Yes	Yes	N/A	Yes	Yes	Yes	Limited	N/A	Yes
MIX_{And}, Andersen et al. [245]	N/A	Yes	Yes	Yes	Yes	Yes	Yes	Limited	N/A	Yes
Shah and Furbo [246]	N/A	Yes	Yes	Yes	Yes	Yes	N/A	N/A	N/A	Yes
Huhn [247]/van Berkel [248]	N/A	Yes	Yes	Yes	Yes	Yes	N/A	Yes	Yes	Yes

and energy efficient materials and systems would work for achieving sustainability in buildings.

As stated in the earlier section that TES systems are much preferable for low energy buildings, MacCracken [258] discussed the merits of TES for buildings equipped with conventional chilled water system for providing cooling to indoor spaces. The TES system proposed actually contributed for peak load shaving and reduced the possibility of over sizing the chillers based on design safety factors. TES system can be prioritized not just because they would shift on-peak load to off-peak hours but to actually utilize useful power available at low cost to charge the TES during night hours for satisfying cooling load in daytime. Furthermore, incorporation of cost-effective TES system with chiller plant meets out about 20% of design cooling load rather than uplifting the capacity of chiller plant by 20% higher than the actual demand. Typically this trend would reduce the overall electrical power consumption and render green design with LEED credits to buildings without compromising on the energy efficiency and net cost-energy savings [259].

Wang and Zhao [260] outlined the trend of electrical power consumption in China and suggested for installing TES systems in buildings which seems to be a great challenge among engineers and architects. In the last decade it is approximated that 60 new TES installations were done, of which 20 TES systems were built-in Beijing for providing heating in buildings. These systems were capable of addressing hot water demand in buildings. They suggest for much more TES system installations in China, but that necessitates for the intense research work as well as manufacturers having matured technologies to promote these systems. From the perspective of leading manufacturers in this field, ice-CTES system coupled with chiller plant is seen to be the ideal candidate for shifting peak load demands to part load hours. Because of the inherent thermal characteristics exhibited during charging/discharging processes and cost-energy savings potential more emphasis has been given for developing these systems for medium to large scale building assignments. Moreover, as they utilize water (mixed with ethylene glycol in proper proportions) as the PCM and normal chilled water as HTF it adds more green credits to its successful implementation in buildings [262].

Buildings (either new or refurbishment) that has to be tuned for accredited with LEED certification has to pass through the three major static and dynamic performance parameters, i.e. water efficiency, indoor environmental quality (IEQ) and energy efficiency. The LEED credits designated for these parameters are well presented by Tseng [261]. In order to achieve LEED certifications for buildings equipped with LHES/CTES systems they must qualify the minimum requirements set forth in the rating system. Generically, the minimum point's level assigned for buildings to go green is in the range of 26–32. For Silver rating, Gold and Platinum ratings the point's level rise to 33–38, 39–51, 52–59 respectively [263]. Apart from other energy conservative measures accounted in buildings, effective amalgamation of LHES and CTES systems with cooling/heating plants would indubitably earn LEED credits to the building.

Detailed design methodologies, testing procedures and thermal performance analysis of LHES and CTES systems have been standardized in order to ascertain the inherent operational characteristics of these systems for varying thermal load conditions [266–269]. Furthermore, much information can be obtained on the latest trends in TES technologies making use of advanced PCMs and other heat storage materials and case studies of buildings equipped with TES systems that are certified with LEED credits from [270–284].

As a valid measure to develop and improve the overall performance of TES systems, value-added designs and selection of appropriate heat storage materials would pave way to achieve

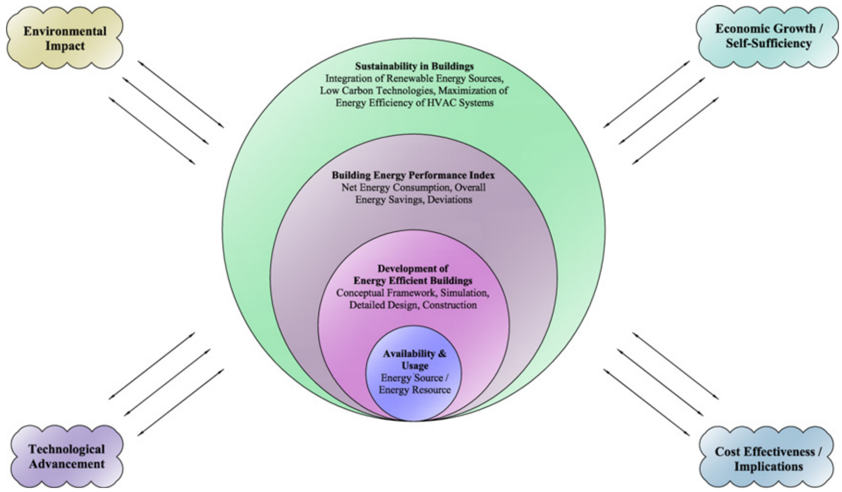


Fig. 27. Sustainability chart for the development of energy efficient buildings.

energy efficiency and sustainability in buildings. The sphere of sustainability as shown in Fig. 27 explains how the various crucial parameters starting from the energy source availability to the maximization of energy efficiency in buildings are interconnected to each other by means of technological, socio-economic, environmental and cost-effective measures.

5.5. Scope for future research

In the pathway of research oriented towards developing TES systems for modern building cooling/heating applications, it is evident that huge potential is available for exploring innovative thoughts and means for producing the energy efficient and sustainable TES systems. Some suggestions and recommendations for further research are included here:

- Detailed transient analyses of thermal properties, heat transfer mechanisms between PCM and building fabric elements needs attention in terms of real time experimentation than validating the numerical models based on previously established numerical solutions.
- Thermophysical properties found in PCMs have to be improved further by reducing the effects of supercooling, agglomeration and nucleation during phase change process. Chemical and thermal reliability of heat storage materials to be evaluated using various combinations of heat transfer enhancement methodologies.
- Performance assessment of various combinations of PCMs with other sensible heat storage methods to enhance the overall energy efficiency of building HVAC systems.
- Develop hybrid cool thermal partial energy storage A/C systems that would achieve the merits of a full energy storage A/C system that would ensure energy efficiency in buildings as well.
- Combine the merits of energy efficient cold air distribution and CTES A/C systems for acquiring improved heat storage capabilities through performing advanced materials science research.

6. Conclusions

The impact of global energy consumption has geared up for the development of efficient, reliable and sustainable energy technologies wherein TES has a major role to par the gap between the energy supply and energy demand. In the modern technological era, with the rising energy challenges and climate change, reducing the energy consumption per square foot has become a perquisite in almost all buildings starting from the scheme design to the construction stage. Higher energy consumption in buildings may be due to the following reasons:

- ambiguities involved in design, construction and commissioning of buildings, use of less efficient cooling, heating and ventilation systems for routine operations, depend more on conventional energy source based systems rather than implementing renewable energy driven systems, and
- improper functioning of intelligent building management and control systems.

Many research studies were performed to address the energy related issues and have come out with different technical solutions for reducing its adverse effects in the society. TES systems can be regarded as a green solution to confront the higher consumption of fossil based energy sources, since it utilizes the electrical energy available at off-peak periods for charging. Having considering these aspects, several research teams dedicated their efforts for the development of LHES and CTES systems and the survey done here on those studies have led to the following conclusions:

- energy storage and release capacities of PCMs mainly depends on its thermophysical properties and stability to chemical, thermal and mechanical degradation effects.
- Fusion temperatures of PCM vitally characterize the degree of comfort in indoor environments for passively designed buildings. Arrangement of PCMs in building interiors such as on wall, underfloor, ceiling void, roofs etc. establish a range of comfort levels and reduce the temperature swings in interior space accordingly.
- Various numerical simulations and experimental validations done for passive LHES systems in buildings necessitate the transition temperature of PCMs to be in the range of 22–28 °C. For active CTES systems, the degree of ice formation for ice-based system, stratification efficiency of storage tank for chilled water system, mass flow rate and heat exchange mechanism of PCS for ice slurry systems decides their performance and energy efficiency.
- Difficulties identified in using the heat storage materials have been demonstrated. PCMs capable of enhancing heat transfer mechanisms have been pointed out which enables one to select the appropriate PCM for designing energy efficient LHES systems for building cooling and heating applications.
- Micro and nanoencapsulated PCMs behaves far superior than the conventional organic, inorganic or eutectic PCMs and exhibits

enhanced latent heat storage and release densities during melting and freezing cycles.

- It is emphasized that PCM based TES systems are more energy efficient while compared to other heat storage systems in its class. But, these systems would render cost implications. A possible way to make them cost effective is to opt for synthesis and preparation techniques related to micro level and nanoscale fabrication.
- Based on the collective information presented from numerous research studies, it is fairly estimated around 10–15% of space conditioning energy savings potential can be accomplished for passively designed buildings incorporated with LHES systems. Likewise, for buildings equipped with active CTES systems the energy savings are expected to achieve around 45–55%.
- Overall energy-cost savings can be possible in buildings on long term basis, if it is being functionalized with highly energy efficient TES system operations and measures without sacrificing the built-in comfort to the occupants. Further research investigations are actually required to standardize the performance of LHES and CTES systems to work out its effectiveness in buildings located at different climatic regions.
- In total, the usefulness of LHES and CTES systems from the view point of research outcomes as presented here indicates a positive sign towards delivering good comfort conditions to occupants in indoor environments. The energy efficient operation and reduced GHG emissions of TES collectively minimize the impact on the environment and would help to achieve sustainability in both buildings and environment.

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